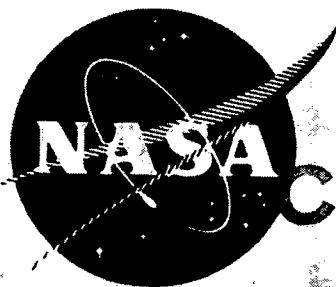


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DEVELOPMENT OF A METALLIC BELLOWS EXPULSION DEVICE FOR FLUORINE SERVICE

by

R. F. Fearn

MARTIN MARIETTA CORPORATION

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

CONTRACT NAS3-12053

R. E. Grey, Project Manager

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NASA CR-72980

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FINAL REPORT

DEVELOPMENT OF A METALLIC BELLOWS
EXPLUSION DEVICE FOR FLUORINE SERVICE

by

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

October 1971

CONTRACT NAS3-12053

NASA Lewis Research Center
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Chemical Rocket Division

FOREWORD

This report is submitted in accordance with the requirements of Contract NAS3-12053 to document results obtained in development of a metallic bellows expulsion device for use with liquid fluorine.

The program was conducted under the technical direction of Mr. R. E. Grey (NASA LeRC); Mr. R. F. Fearn (Martin Marietta Corporation) served as the program manager. Acknowledgement is made of significant technical contributions made by the following Martin Marietta personnel:

J. S. Marino	Design
L. J. Rose	Test
A. T. Pecarich	Test
F. J. Galyean	Fabrication
A. E. Blair	Instrumentation

ABSTRACT

This program was conducted to demonstrate the feasibility of using metallic bellows to expel liquid fluorine. To achieve this objective, a complete expulsion device was designed, fabricated, and tested in accordance with requirements specified by NASA. Difficulties were experienced in obtaining leaktight welds at the bellows end terminals, but eventually three assemblies were successfully fabricated and cycle tested, one in LN_2 , two in LF_2 . The bellows performed well, except that they failed prematurely (less than 50 cycles) in LF_2 , apparently the result of small initiator cracks in the seam welds of the bellows.

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SUMMARY

The primary objective of this program was to demonstrate satisfactory performance of a metallic bellows positive expulsion device in liquid fluorine (LF_2). This objective was to be achieved by designing, fabricating, and testing a device in accordance with design requirements provided by NASA.

The major portion of the program was conducted by Martin Marietta, but the bellows was designed and fabricated (including the end joints) by DK-Aerospace under contract to Martin Marietta. A major difficulty was experienced in welding the stainless steel bellows to the end terminals, but three acceptable assemblies were fabricated by DK-Aerospace following a change in the bellows material. One of these assemblies was cycle tested in liquid nitrogen (LN_2) to verify cycle life and hardware integrity, and provide a means of developing test techniques under relatively safe conditions; the other two were subsequently tested in LF_2 . A cycle life of at least 400 cycles was predicted, though it was planned to subject the bellows to only 100 cycles in LF_2 .

The bellows performed well, and no significant difficulties were experienced with the test hardware. However, the bellows tested in LN_2 failed (developed a fatigue crack) in approximately 250 cycles; and two tested in LF_2 failed in less than 50 cycles. The precise cause of these premature failures is not known. The cycle test results indicate that fluorine may have had an adverse effect on cycle life, but the available statistical evidence is insufficient to permit firm conclusions to be drawn. Cycle life could probably be improved significantly by fabricating the bellows from seamless tubing rather than seam-welded sheet material. All failures occurred in the seam welds where subsequent metallurgical examination revealed the presence of many small initiator cracks, apparently resulting from the convolute forming process. Metallurgical examination, however, did not prove to be a satisfactory technique for identifying the presence (or absence) of stress corrosion.

It is concluded that metallic bellows positive expulsion devices are generally suitable for use with liquid fluorine (or other highly reactive propellants), but the cycle life is not accurately predictable. There appears to be a need for further work in this area to quantitatively determine the influence of chemical reactivity, cryogenic temperature, working pressure, and seam welds on bellows cycle life.

I. INTRODUCTION

The program described in this report was conducted to demonstrate the feasibility of using metallic bellows devices for the expulsion of liquid fluorine, flox or lox. The device that was fabricated and tested was not designed for a specific application, but rather, to satisfy a representative set of performance requirements specified by NASA. Testing was conducted with fluorine because it presents the most severe handling problem of the three propellants.

Metallic bellows have been used in a number of different positive-expulsion applications during the past few years. These devices offer certain inherent advantages over competitive devices using bladders and diaphragms, but also possess some disadvantages. They do assure positive liquid expulsion under all conceivable operating environments (assuming no propellant vaporization), can be made compatible with any fluid of interest, can provide high expulsion efficiencies in the range of 98 to 99%, and have a relatively high cycle life. Their primary disadvantages are relatively high weight, limited configuration flexibility, and relatively high cost (particularly to develop tooling for new configurations).

One of the predecessors to the specific expulsion device tested in this program is a device designed by Solar for LH₂ service. This device contained a stainless steel bellows with a mean diameter of 13 in. (0.330 m) to expel LH₂ at a expulsion efficiency of approximately 98%. It was successfully tested by Martin Marietta late in 1968 under contract to NASA.

An even closer configuration to the bellows tested in fluorine is one that has been used successfully in an Air Force program to expel storable propellants. This bellows is also of 13 in. (0.330 m) nominal diameter; but its design was based on different requirements regarding total displacement, cycle life, and propellant compatibility. By adopting this same basic convolute configuration, it was possible to produce the fluorine bellows without entailing significant development costs. Using tooling of proved design, it was only necessary to experiment with such fundamental parameters as material thickness and number of convolutions to obtain a suitable bellows design.

The program was conducted in three major phases; i.e., Task I, the design of the expulsion device; Task II, fabrication and proof testing of the device (including three bellows assemblies); and Task III, cycle testing of the bellows in both LN₂ and LF₂. Welding the bellows to the end terminals proved to be a formidable task, but otherwise, the program was accomplished without major difficulties. Although the bellows did not fully satisfy design expectations (the cycle life was less than anticipated), the general feasibility of metallic bellows for fluorine service was satisfactorily demonstrated. Consequently, it appears that metallic bellows can be designed to service almost any conceivable propellant.

The chapters of this report are organized in a manner compatible with that in which the program was actually conducted; i.e., in chronological order (design, fabrication, and testing). Following the design task (Chapter II), Task II is presented in two parts, i.e., fabrication (Chapter III) and proof test (Chapter IV). Task III is presented in four parts, i.e., cycle test apparatus (Chapter V), LN_2 cycle tests (Chapter VI), LF_2 cycle tests (Chapter VII), and postcycle tests and failure analysis (Chapter VIII). These are followed by a discussion of results (Chapter IX) and Conclusions (Chapter X). The formal test procedure that was evolved for the cycle tests is contained in the appendix.

In accordance with contract requirements, the International System of Units (ISU) is included in the report as a secondary system. The vast majority of the measurements were taken in English units, consequently the primary presentation of data is in English units. The equivalent ISU quantities are included in the text in parentheses following the English units, and as secondary scales on the data plots.

II. EXPULSION DEVICE DESIGN

The primary goal of the design effort was to evolve the detailed design for a metallic bellows positive-expulsion device, based on performance specifications provided by NASA-LeRC. These specifications included many requirements regarding working pressure, expulsion volume and efficiency, leakage and cycle life; however, the most critical design requirement was that the device be suitable for expulsion of liquid fluorine. Proof of design adequacy was to be demonstrated by fabricating several of the assemblies and testing them under design conditions with liquid fluorine.

The overall design was developed by Martin Marietta. However, the most critical component, the bellows, was designed principally by DK-Aerospace under contract to Martin Marietta. The joint between the bellows and its end terminals was also designed by DK-Aerospace based on their prior experience with a similar bellows assembly. Although many constraints were placed on the bellows design to minimize developmental problems and costs, some latitude still remained in evolving a design that would satisfy the performance specifications.

As the design task progressed, it became evident that available analytical tools for designing the bellows were not entirely adequate, particularly with regard to cycle life. The state of the art is such that a straightforward explicit solution to the problem is not possible, although qualitatively the influence of the major parameters is fairly well understood. In spite of this, a sound design was developed that later satisfied the majority of the performance requirements, except that the actual cycle life was far below the design goal. Designs were also developed for two fixtures used in acceptance and proof testing of the bellows.

To provide some insight into the features that might be incorporated into an expulsion device for flight applications, a preliminary design was evolved for a flight article having a configuration similar to that of the test article. Pertinent features of the test article are discussed in Sections A through H; the flight article is briefly described in Section I.

A. DESIGN SPECIFICATIONS

The specific requirements imposed by NASA on the design are as follows:

- 1) Capacity (expulsion volume): 0.5 to 1.0 cu ft (0.014 to 0.028 m³);
- 2) Length-to-diameter ratio: 0.5 to 1.5;
- 3) Configuration: flanged pressure vessel for convenient replacement of bellows assemblies;
- 4) Expulsion efficiency: 98% minimum;

- 5) Propellant delivery (expulsion pressure: 150 psig (103 N/cm², g);
- 6) Bellows internal (fill) pressure; 20 psig (13.8 N/cm², g);
- 7) Cycle life: 1000 cycles;
- 8) Leak rate maximum: 10⁻⁶ Scc He/sec;
- 9) Materials: compatible with liquid fluorine, floc, and lox;
- 10) Bellows: formed convolutions (welded convolutions not acceptable);
- 11) Proof factor: 1.75 at LN₂ temperature (78°K).

In addition to the foregoing performance requirements, several other guidelines played an important part in the evolution of the design. These were as follows:

- 1) The device was designed as a test article to prove a design concept. The major portion of the device actually serves as a test tool for testing the bellows. It is not flight-type hardware, therefore, it was overdesigned from a structural standpoint;
- 2) Consistent with standard practices for producing test hardware, emphasis was placed on design features that resulted in low cost, ease of fabrication, and simplicity of assembly and test;
- 3) The bellows design was based on current state-of-the-art design techniques. No attempt was made to advance the state of the art.

B. MATERIALS SELECTION

Considerable latitude existed with regard to the selection of materials for the positive expulsion device even though a requirement for both chemical and cryogenic compatibility must be satisfied. In general, materials that are chemically compatible with fluorine are also suitable for cryogenic service, so the selection is not narrowed significantly by these dual requirements. Nickel and Monel provide compatibility over the widest range of conditions, but copper, brass, aluminum, and stainless steel alloys are also acceptable over fairly wide ranges of temperatures and pressures. Titanium alloys have superior structural characteristics, and are also reasonably compatible with fluorine, but they were considered too expensive and too difficult to fabricate to receive serious consideration for use in this device. Copper and brass do not possess good structural properties, and thus did not receive serious consideration either. In addition to compatibility, other important factors that were taken into account include strength, formability (particularly for the bellows and domes), weldability, and availability.

Considering the above factors, it was decided early in the program that 300-series stainless steel would be used for both the bellows and the other major components of the expulsion device. Extensive experience has been

acquired with stainless steel in a variety of fluorine applications, and bellows applications, so this provides a conservative approach. To minimize stress corrosion, however, it was necessary to select either the stabilized alloys (Type 321 or 347), or those with very low carbon content such as Type 304L.

C. GENERAL CONFIGURATION

The general configuration evolved for the device is typical of that employed for bellows expulsion devices. It consists principally of a pressure vessel fitted with an internal bellows assembly that serves as a seal to separate the propellant (fluid to be expelled) from the pressurization gas. The propellant is contained within the bellows assembly; the pressurization gas acts on a movable dome attached to one end of the bellows to displace the dome (and the propellant) until the dome eventually comes to rest against the fixed end dome of the pressure vessel. By careful control of clearances, the fluid finally trapped within the bellows convolutions and in other clearance spaces is minimized, i.e., a high expulsion efficiency is attained.

The general configuration described above can be achieved in a number of different ways with regard to placement of the required flanged joint, and details of the various domes and related joints. After considering the many options available, the basic configuration shown in figure 1 was proposed for this particular application. In this design only three domes are required (four are required in some cases), and only two of these must actually nest together with a close tolerance fit. Therefore, the complexity and cost of the assembly are held to a minimum.

To further simplify the design and reduce tooling costs, it was also decided to use the same basic dome configuration for both ends of the pressure vessel (the convex fixed dome of the bellows assembly serves as one end of the vessel). The only significant disadvantage of this approach is that the movable dome cannot be made to nest against the inverted end dome when the bellows is in the fully extended position. Consequently, the device will have a larger ullage volume than otherwise required, and the movable dome must be slightly heavier so that it can withstand the 20 psig (14 N/cm^2 , g) internal "fill" pressure without collapsing. The final configuration requires only two basic domes. One of these is a standard dome shape used at both ends of the vessel, the other is a special movable dome that is designed specifically to nest in one of the other domes.

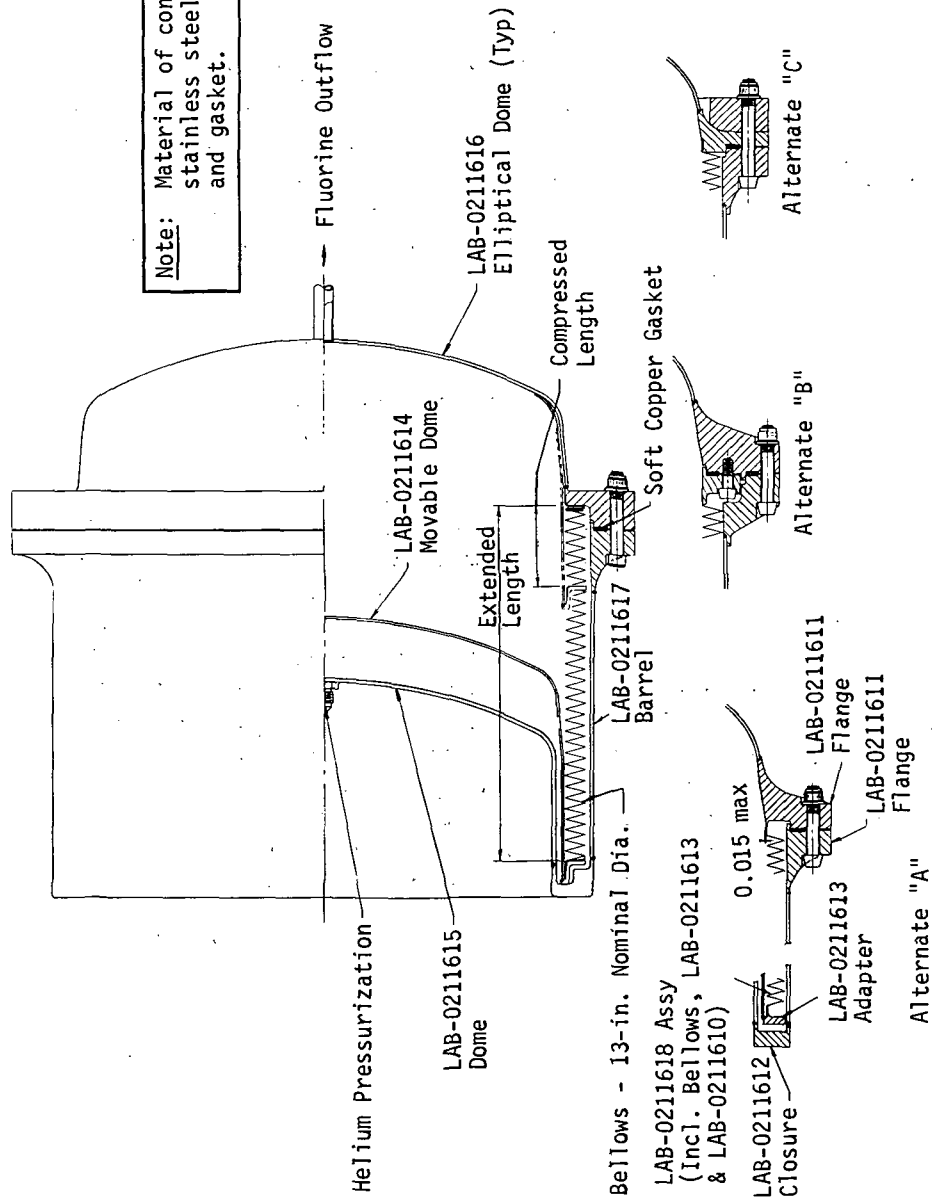


Figure 1 Preliminary Design of Expulsion Device (LAB-0211604)

The final design that evolved from the earlier conceptual design is presented in figure 2. This configuration is characterized by the following features:

- 1) A butt joint (Alternate A of fig. 1) was selected to join the bellows to the end terminals in preference to a lap-joint. The butt joint is considerably more difficult to make, but it provides a smooth surface both inside and out so that no compatibility problems will arise even if the bellows should develop leaks;
- 2) The flanged joint incorporates a three-piece design (Alternate C of fig. 1) instead of two pieces. This feature results in a lighter weight bellows assembly for easier handling. Much of the mass required to provide joint stiffness is contained in the backup flange (only one is required), which can be handled separately;
- 3) A two-piece design was selected for the guide ring at the movable end of the bellows for more convenient final assembly. The inner sleeve on the ring is machined to provide a final adjustment of the bellows compressed length; the final closure weld of the assembly has been located on the outside diameter of the ring for maximum accessibility.

D. BELLOWS CHARACTERISTICS

The problem of developing a bellows design that satisfies the specific performance requirements previously presented proved to be a formidable one. It might be expected that relatively simple mathematical relationships exist to relate the performance characteristics of the device to the pertinent bellows parameters, but this was not found to be the case. Analytical techniques have been developed for computing bellows stresses, but they are relatively complex, and must be supplemented by empirical data. In addition, stress analysis of the bellows neck (transition region between the end convolution and the joint with the end terminal) presents a very difficult problem. Consequently, it is necessary to rely heavily on empirical data for the prediction of bellows performance, particularly cycle life. Some experimental data did exist for the bellows configuration selected for this application, but it was not extensive, so the performance characteristics of the bellows could not be predicted with great accuracy.

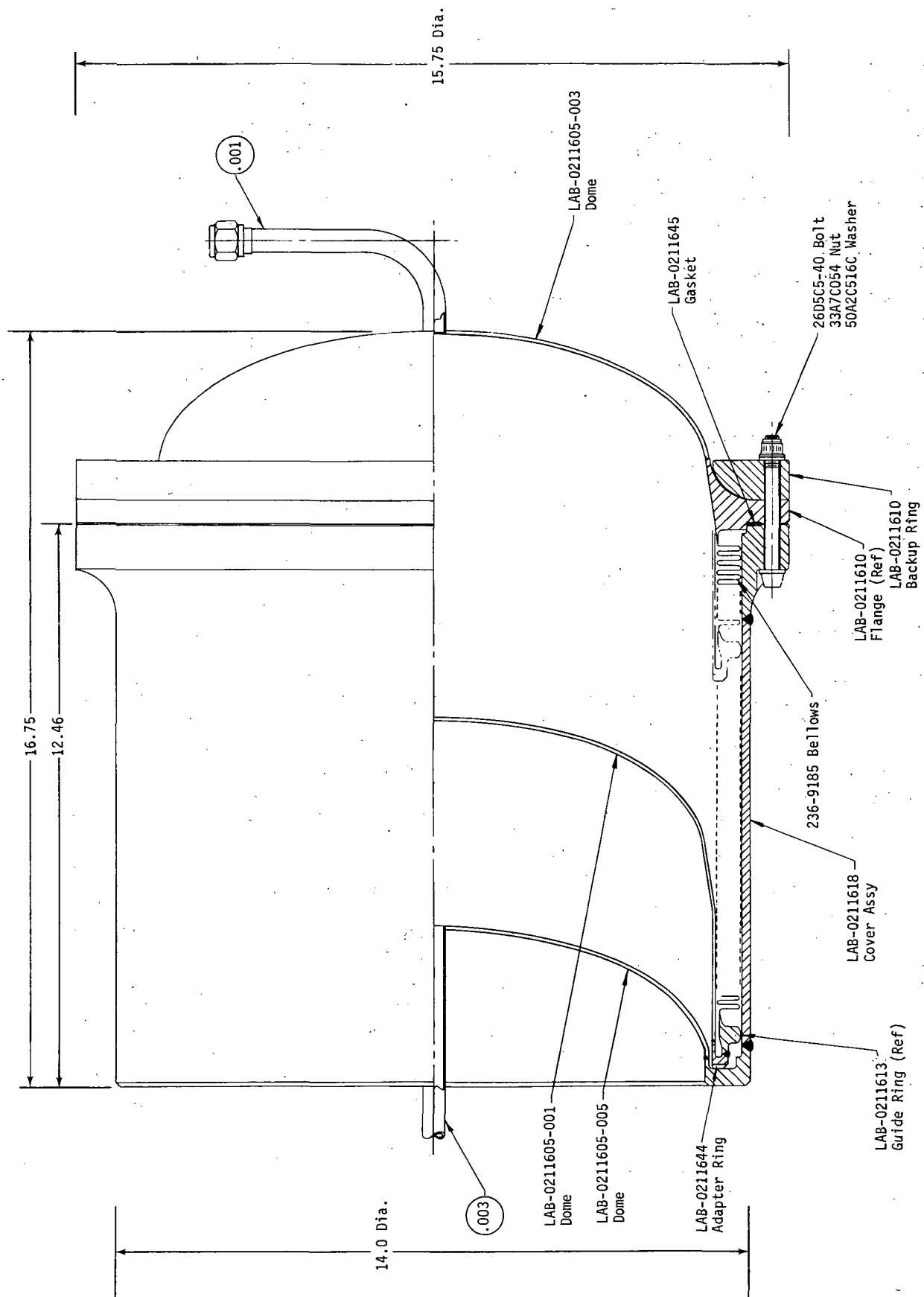


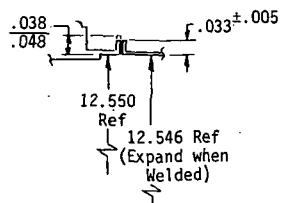
Figure 2 Positive Expulsion Device

The major parameters that enter into bellows design include material mechanical properties, thickness, nominal diameter, span, contour of the convolutions, and the number of convolutions (which is related to the stroke and the ratio of extended to compressed length). Some of these parameters realistically may be treated as variables in an attempt to achieve the desired performance characteristics, but many of them are in reality essentially fixed by the practical factors involved. In this particular program stainless steel was selected for practical reasons, hence the material mechanical properties were essentially fixed. Also, for practical reasons, it was necessary to use existing bellows tooling and fabrication experience to the fullest extent possible. Specifically, this meant using bellows with a nominal 12.5 in. (0.317 m) I.D. and 13.5 in. (0.343 m) O.D., a size that had been previously developed for an Air Force application. Several different bellows fabricators had satisfactory tooling for this particular size, and acquired a backlog of fabrication and test experience.

The bellows span was also fixed by available tooling, and was not a parameter to be varied to alter bellows performance characteristics. Likewise, the contour of the bellows convolutions is fixed by the available tooling. Some latitude presumably does exist in the selection of bellows contour because different fabricators have developed different tooling that produces different contours, but the choice is very limited. Once the fabricator was selected (DK-Aerospace was selected in this case because of their experience with butt-joints at the end terminals), the contour was fixed. The approximate contour of the DK-Aerospace bellows (in the relaxed position) is included in figure 3.

Thus, the only significant bellows parameters that can be varied are the material thickness and the number of convolutions. These parameters are manipulated to best satisfy the design objectives related to expulsion volume, expulsion pressure, internal fill pressure, cycle life, and expulsion efficiency. The design effort at this point was found to be primarily a cut-and-try process; i.e., choose a set of design parameters, then estimate the various performance characteristics as accurately as possible, using the limited design tools that were available.

Material thickness was selected after considering two principal factors, i.e., the limitation imposed by practical fabrication techniques, and the buckling loads imposed on the bellows neck. Although it might be expected that the bellows thickness would be largely determined by the expulsion pressure, this is not the case. The bellows is subjected to a high external differential pressure at the end of expulsion, but this does not represent a critical operating condition for the bellows convolutions. At this time the bellows is in the compressed condition with the convolutions tightly packed together. Hence, it is not a simple thin-walled cylinder, but consists of a stack of annular disks interconnected at the inside and outside diameters. The resistance of this complex configuration to externally applied pressures is very difficult to analyze, but experiments conducted by DK-Aerospace have demonstrated that bellows of this general configuration will withstand pressures much greater than the 262 psig (200 N/cm^2 , g) proof pressure.



Welding Detail



Figure 3 Bellows Subassembly

Purely practical considerations dictated the the bellows thickness be at least 0.005 in. (0.13 mm). Thicknesses less than this would be exceedingly difficult to weld, and would require additional tooling development to obtain the desired contours at the convolution roots and crests. At the same time, a rough analysis of the buckling loads on the bellows neck indicated that a thickness of 0.007 in. (0.18 mm) was the minimum that could be tolerated.

The method used to perform the buckling analysis is outlined in ref. 1. It strictly applies only to "simply supported" thin-walled cylinders, but should provide a conservative estimate for the bellows neck which is supported fairly rigidly by a weld joint at one end, and by a convolution "disk" at the other. For a 0.156-in. (3.96 mm) long neck (the minimum length that can be welded using available tooling and techniques), the "z-factor" identified in ref. 1 is computed as follows:

$$z = \frac{\ell^2}{rh} \sqrt{1 - \nu^2} = 0.5$$

where

ℓ = length of cylinder (in.),

r = radius of cylinder (in.),

h = thickness of cylinder (in.),

ν = Poisson's Ratio.

Then, from the plot of z versus k_y (ref. 1), the value of k_y is found to be 4. Substituting this in the equation for critical buckling pressure:

$$P = \frac{\pi^2 E h^3 k_y}{12 (1 - \nu^2) r \ell^2}$$

$$= 245 \text{ psi (168 N/cm}^2\text{)}$$

Since the proof pressure is slightly greater than this, the 0.007 in. (0.18 mm) thickness is somewhat marginal. However, as noted above, the bellows neck is not just a "simply supported" cylinder. In addition, reference 1 notes that "short cylinders can sustain significant pressure increases after buckling and before collapse." Because of this and the fact that increasing the thickness beyond 0.007 in. (0.18 mm) would have an undesirable effect on cycle life, 0.007 in. (0.18 mm) was selected as the thickness.

With regard to the number of convolutions to be used, a trial and error approach by DK-Aerospace finally resulted in the selection of 35 convolutions to provide a stroke of 8.5 in. (0.216 m) or 0.24 in. (6.1 mm) stroke/convolution. To prevent crushing of the convolutions when in the compressed condition, DK-Aerospace experience indicated that a minimum pitch of 0.050 in. (1.27 mm)

must be maintained. For 35 convolutions, this results in a bellows compressed length of 1.75 in. (4.45 cm). Consequently, the extended length is 10.25 in. (0.26 m). The selected stroke of 8.5 in. (0.216 m) provides a displacement of 0.657 ft³ (0.0186 m³), well within the specified range of 0.5 to 1.0 ft³ (0.014 to 0.028 m³).

The selection of the number of convolutions was based primarily on the cycle life requirement, then checked for compliance with other requirements. Actually the best experimental data that DK-Aerospace had available indicated that the expected cycle life was somewhat less than 1000 cycles. Four bellows of similar design had been cycled over an equivalent range of stroke per convolution to produce failures after 481, 571, 821, and 985 cycles. A conservative estimate of the minimum cycle life to be expected, based on these test results, is 400 cycles, a value considerably less than the design goal of 1000 cycles. On the other hand, this lower cycle life is still considerably greater than the number of fluorine cycle tests planned, so it was accepted as a reasonable compromise to be able to achieve other design goals. No allowance was made for the possible influence of cryogenic temperature or chemical reactivity on cycle life. This was not an oversight, but rather the result of not having technical data pertinent to the problem.

The selected bellows configuration also failed to fully satisfy expulsion efficiency requirements. To achieve the specified expulsion efficiency of 98% for the expulsion device, it was desired to limit the trapped liquid volume within the bellows convolutions in the compressed condition to 1% of the displacement; i.e., 11.3 in.³ (185 cm³) thereby allowing an additional 11.3 in.³ (185 cm³) volume for other liquid trapped between the movable dome and the other wetted surfaces. With the aid of figure 4, an approximation of the trapped volume within the bellows for the final design may be calculated. Since the bellows pitch in the compressed condition is 0.050 in. (1.27 mm), and the metal thickness is 0.007 in. (0.18 mm), the effective "thickness" of the trapped liquid in the annulus (assuming it to be one-half the total trapped volume) is $\frac{0.050 - 2(0.007)}{2} = 0.018$ in. (0.46 mm) per convolution. Further, since the cross-sectional area of the convolutions is 22.1 in.² (142 cm²) and there are 35 of them, the trapped liquid volume is 14 in.³ (229 cm³). It will be noted that this volume is nearly 1½% of the bellows displacement, leaving only 8.5 in.³ (139 cm³) for other trapped volumes. This is the best compromise that could be reached.

Another factor that was considered in the bellows design was the requirement that the bellows withstand an internal "fill" pressure of 20 psig (13.8 N/cm², g). To test the selected design against this requirement, DK-Aerospace employed an equation adapted from the Haringx formula for critical squirm pressure. This equation is as follows.

$$p = \frac{320 r t^3 \times 10^6}{NL b^3}$$

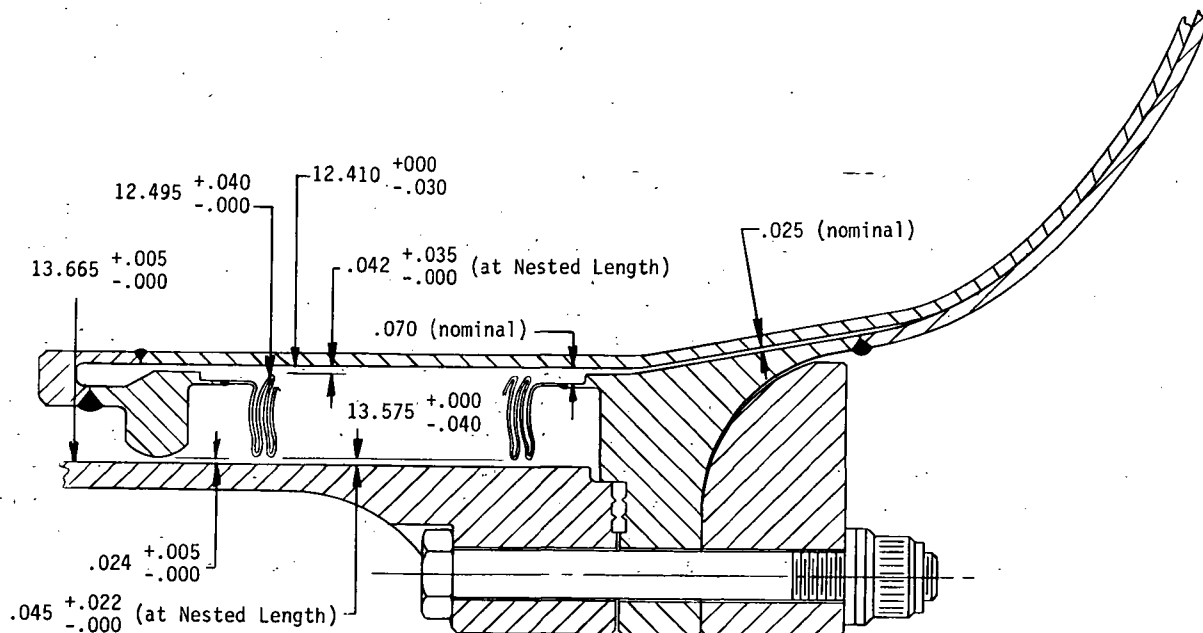


Figure 4 Expulsion Device Clearances

where

p = critical squirm pressure (psig),

320 = is a constant which relates Haringx factors and modulus of elasticity,

r = the bellows outside radius (in.),

t = nominal material thickness (in.),

L = length at maximum extension (in.),

N = total number of convolutes,

b = convolute height (in.).

For the values of r , t , N , and b applicable to the bellows configuration finally selected, the variation of critical pressure with extended length is shown in figure 5. The bellows does not fully satisfy the design requirement for a 10.25-in. (0.26 m) extended length, and the critical pressure is estimated to be only 16.5 psi (10.4 N/cm²) instead of 20 psi (13.8 N/cm²). Therefore, it was necessary to accept a compromise in the bellows performance, but this low allowable internal pressure was not critical with regard to eventual accomplishment of the bellows cycle tests.

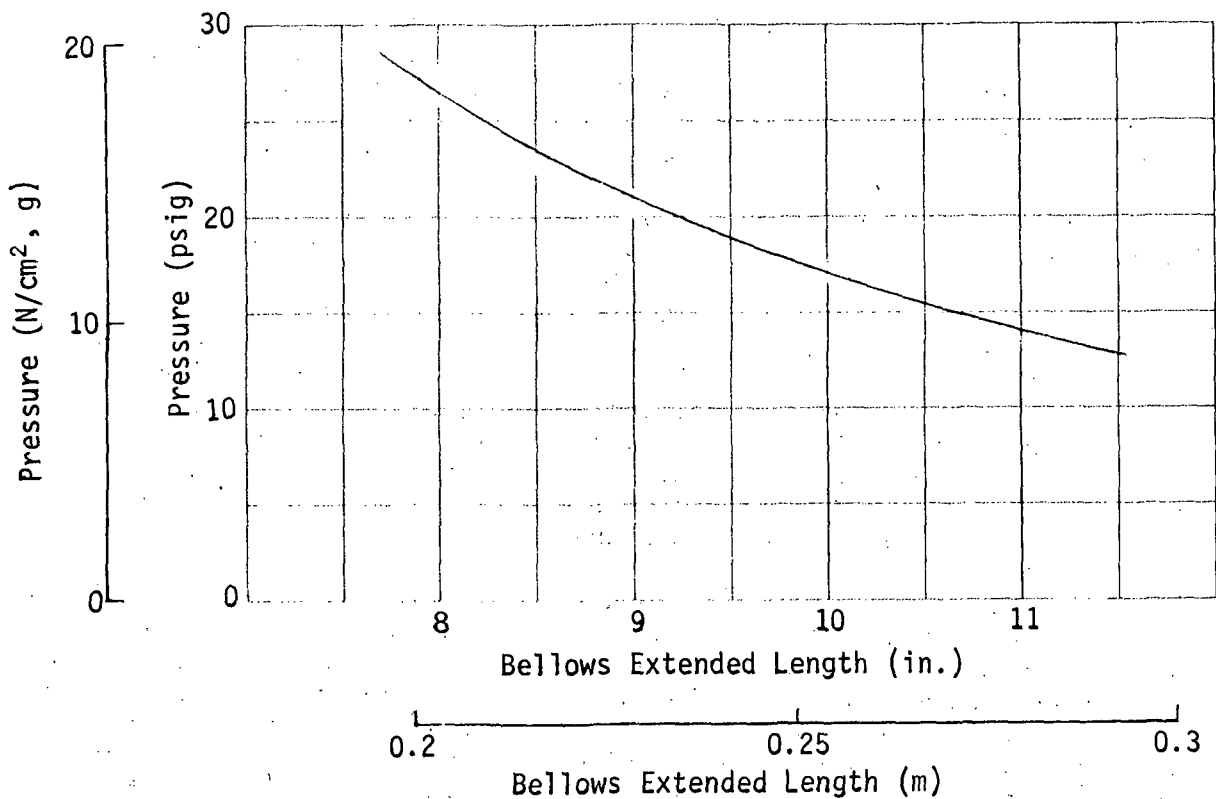


Figure 5 Predicted Bellows Squirm Pressure

A final significant factor that must be considered with regard to the performance of the bellows is the type of tubing employed, i.e., seamless vs seam-welded. Seam-welded bellows consistently fail (develop fatigue cracks) in the longitudinal weld joint, not in the parent metal. Therefore, seamless tubing provides superior performance (greater cycle life), but it is very costly and requires a much longer procurement cycle. From the beginning it was planned to use welded tubing, realizing that significantly greater cycle life could be achieved with the same basic design using seamless tubing. Quantitatively, however, the improvement in cycle life to be expected from seamless bellows has not been established.

E. JOINTS

The joints throughout the expulsion device were designed as TIG welded butt-joints, except for the flanged joint that permits the use of a single pressure vessel with interchangeable bellows assemblies. The use of welded butt-joints eliminates the undesirable crevices that are associated with lap joints, and provides the cleanest possible surface for exposure to the fluorine. In addition, where practical the joints were designed to be welded from the inside to further improve the cleanliness of the surface.

The joints at the ends of the bellows presented a particularly difficult problem because of the thin gage of the bellows material. It is not particularly difficult to produce a joint that is structurally sound, but the joint must also be leakproof. Details of the joint design developed by DK-Aerospace are shown in figure 3. The 0.007-in. (0.18 mm) bellows material is mated to a machined section approximately 0.020 in. (0.52 mm) thick, with lips providing the excess material required for a good fusion joint. Success of the joint largely depends on the tooling used to properly position the pieces and dissipate the heat generated during welding. Based on DK-Aerospace experience with a similar joint, this design appeared to be a good choice, but subsequent attempts to fabricate it met with considerable difficulty.

The single flanged joint that is used in the expulsion device (fig. 2) is based on a proved design used by Martin Marietta in many previous applications. The two sealing surfaces machined in the mating stainless steel flanges each contain two serrations that are 0.025-in. (0.64 mm) deep (high). The gasket that provides the seal is completely enclosed so that it has no opportunity to squeeze out and thereby relieve the clamping pressure. It is made from 1100 series aluminum (essentially pure aluminum) 0.100-in. (2.54 mm) thick. This material was selected in preference to soft copper (also fluorine compatible) because it is softer, and therefore is capable of being sealed with a lower clamping pressure.

The flange assembly is fastened together with 32 high-strength bolts of A-286 stainless steel. The bolts are 5/16 in. (7.94 mm) in diameter and 3-in. (7.6 cm) long. During assembly they are torqued to 200 lb/in. (22.6 N/m to provide a preload of 2200 lb/in. (3850 N/cm) on the gasket.

Structural design of the joint to provide adequate stiffness for sealing the gasket was a cut-and-try process, using relatively common design techniques. Initially, a thickness of 0.080 in. (2.03 mm) was selected for the end dome that is welded to the flange, based on consideration of only the internal pressure load. Subsequent analysis of the bending moments at this joint, however, dictated the use of a 0.100-in. (2.54 mm) thick dome.

Analysis of the joint employed the following equation presented in reference 2:

$$M_o = \frac{M}{l + \frac{\beta h}{2} + \frac{(1 - \nu^2)}{2\beta c} \left(\frac{h}{h_1} \right)^3 \ln \frac{d}{c}}$$

where

M_o = moment at flange/dome joint (in.-lb/in.),

M = applied moment about CG of assembled flange (in.-lb/in.),

$$\beta = \left[\frac{3(1 - \nu^2)}{c^2 t^2} \right]^{\frac{1}{4}},$$

h = depth of flange assembly (in.),

h_1 = thickness of dome (in.),

c = internal radius of assembly (in.),

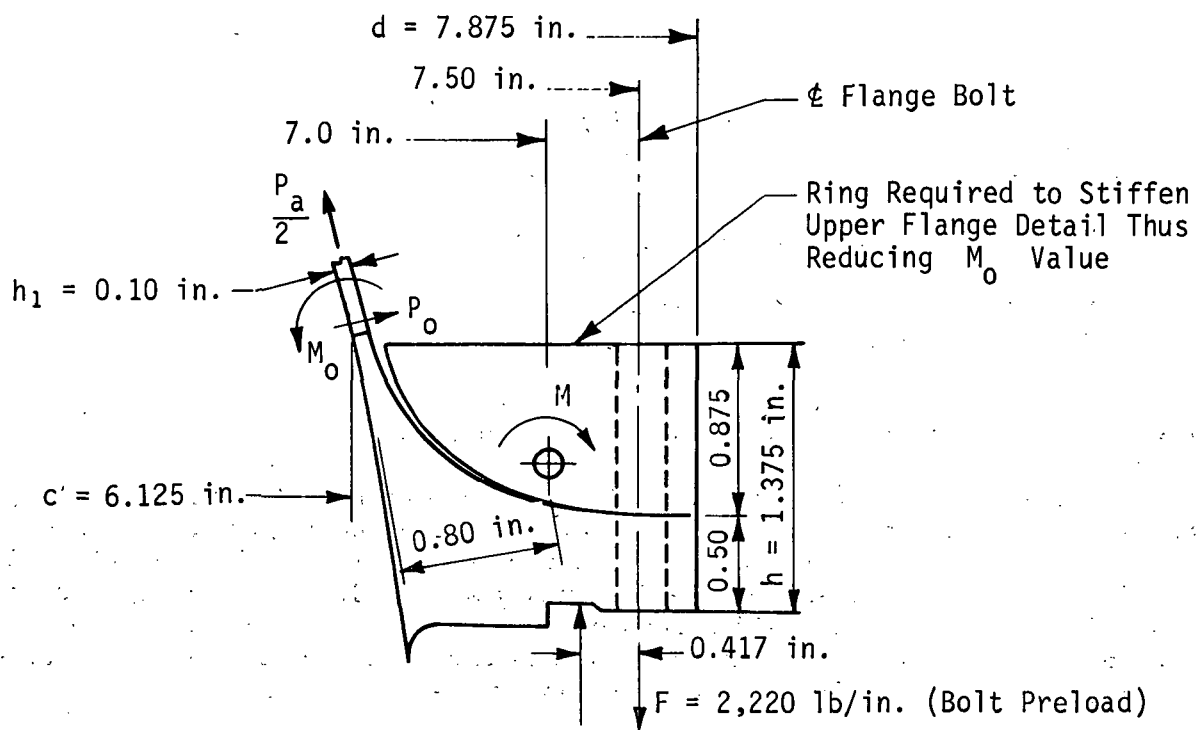
d = external radius of assembly (in.),

ν = Poisson's ratio.

Pertinent dimensions and loads are shown in figure 6.

From the above, the bending moment (M_o) was computed to be 490 in.-lb/in. (2180 N), and the maximum bending stress at the flange/dome joint, 29,400 psi (20,250 N/cm²). This stress combined with a membrane stress of 7800 psi (5380 N/cm²) due to internal pressure, yields a maximum tensile stress of 37,200 psi (25,650 N/cm²). Since the yield stress of 300-series stainless is ~40,000 psi (27,600 N/cm²), it is evident that the assumed dimensional characteristics of the joint are acceptable, but not with an excessive margin of safety.

The joint between the other flange and the barrel of the pressure vessel was analyzed in a similar manner. In this case, the wall thickness of the barrel section was arrived at from purely practical considerations. The standard 14-in. (0.355 m) pipe selected for the barrel, when machined to an I.D. of 13.665 in. (0.347 m) required for proper clearance with the bellows guide-ring, has a wall thickness of ~0.185 in. (4.7 mm). Using this value in the equations yields a moment of 158 in.-lb/in. (703 N) at the flange/barrel joint, corresponding to a bending stress of 27,600 psi (19,000 N/cm²). This stress combined with a hoop stress of 4900 psi (3380 N/cm²) due to internal pressure, results in a maximum tensile stress of 32,500 psi (22,400 N/cm²). Presumably the barrel could be machined to a smaller thickness to reduce the weight somewhat, but this approach would not be of benefit for an item of test hardware.



Gasket Load after Tank Pressurization = 1.434 lb/in.

Figure 6 Upper Flange Details

F. DOMES

The same basic dome shape was selected for both ends of the expulsion device to minimize tooling costs. One is subjected to internal pressure, the other to external pressure. They are of slightly different depths, but otherwise are identical.

The end dome shape selected for this purpose is a standard 12-in.- (0.305 m) diameter dome with a 2-to-1 elliptical contour (fig. 7). The required thickness of one of the domes (exposed to internal pressure) had already been established as 0.100 in. (2.54 mm), based on bending loads imposed by the flanged joint. A simple analysis of the other dome (exposed to external pressure) yielded a critical collapse pressure of 600 psi (414 N/cm²), verifying that the 0.100-in. (2.54 mm) thickness is indeed acceptable for both. To minimize corrosion, Type 304L stainless steel was selected as the dome material.

The movable dome is specially shaped to nest in the fixed end dome (fig. 7), and at the same time provide small clearance volumes with the flange and the bellows I.D. The dome has a 2-to-1 elliptical contour that blends into a short 10 deg (0.175 radians) conical section, then a cylindrical skirt. It is also made of Type 304L stainless steel to minimize corrosion.

The dome thickness was established principally from practical considerations of the weld joint. To minimize problems of heat dissipation during welding, a thickness of 0.080 in. (2.03 mm) was somewhat arbitrarily selected. Stress analyses of the cylindrical section for effects of both internal pressure (when seated at the end of expulsion) and external pressure (when seated at the end of fill) confirmed this thickness to be more than adequate.

The critical dimensions of the movable dome were developed from the requirements of the expulsion device to achieve a 98% expulsion efficiency. The movable dome is designed to provide zero clearance with the end dome, a nominal 0.025-in. (0.64 mm) radial clearance at the conical section, and a 0.042-in. (1.07 mm) minimum clearance at the skirt. Possibly, slightly smaller clearances could be tolerated, but considering out-of-roundness and misalignments that might be encountered during assembly and welding, the selected clearances appear to be more realistic.

Using these design dimensions, the residual liquid volume at the end of expulsion (in addition to the volume within the bellows annulus) may be estimated as shown in the following tabulation.

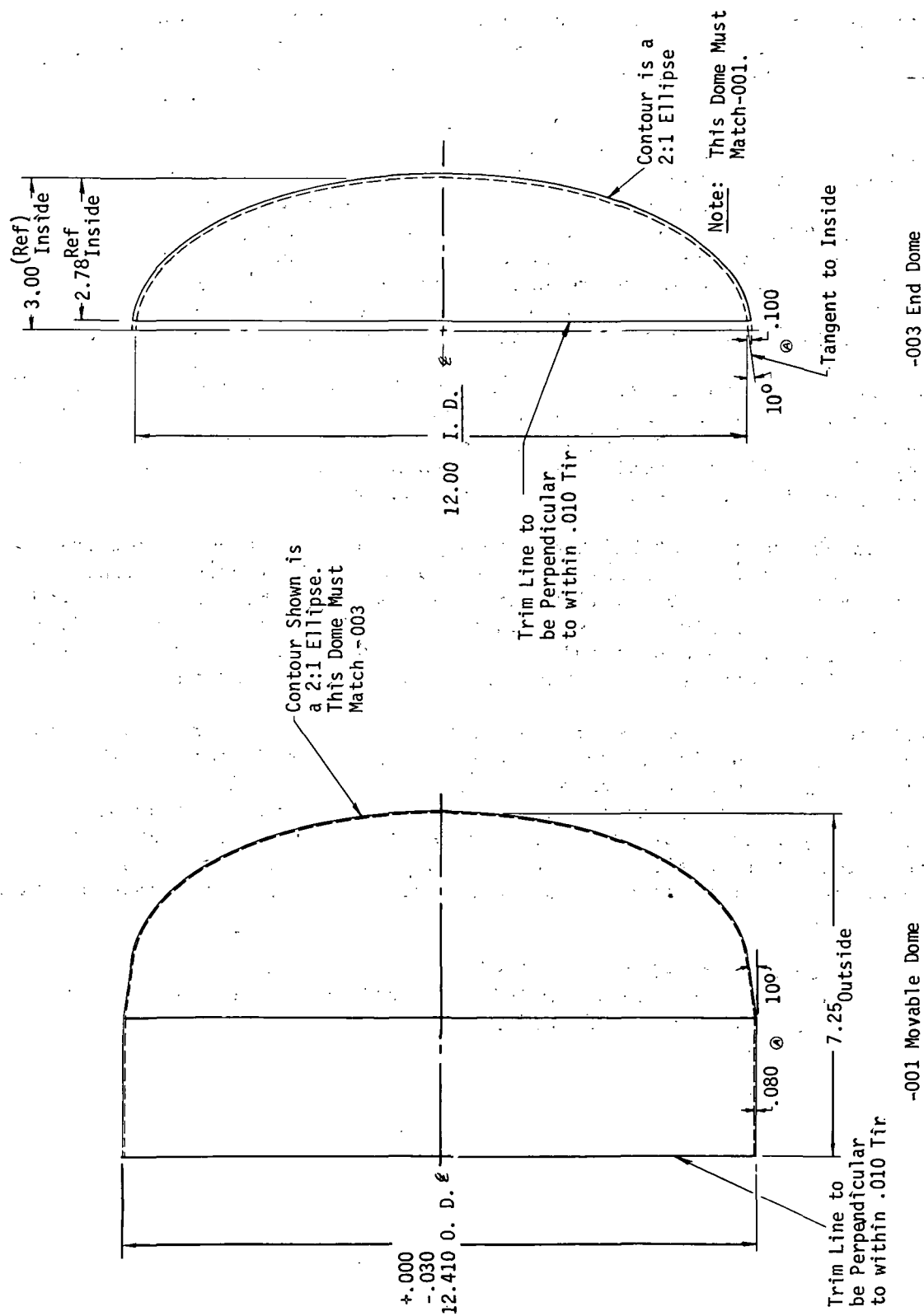


Figure 7 Dome Details

Region	Volume	
	(in. ³)	(cm ³)
Elliptical Dome	0	0
Conical Section	$12.5 \pi (0.025)(2) = 2.0$	33
Bellows ID	$12.5 \pi (0.042)(1.75) = 2.9$	48
Bellows End Joints	$12.5 \pi (0.070)(0.625) = 1.7$	28
Guide Ring	$12.5 \pi (0.100)(0.75) = 3.0$	49
Total	9.6	158

This residual volume amounts to $9.6/1134 = 0.85\%$ of the displacement volume, which combined with the residual volume of the bellows annulus ($1\frac{1}{2}\%$) results in a total residual volume that is 2.1% of the displacement volume. Consequently, the expulsion device would be expected to demonstrate an expulsion efficiency of ~98% if the actual dimensions were the same as the design values. However, because of the relatively large "plus" tolerance on the clearance volumes, the actual efficiency would probably fall slightly below 98%. It might be noted that the effect of cryogenic temperatures on the clearance dimensions will be negligible because all major components are made of the same material, i.e., 300-series stainless steel.

G. OTHER COMPONENTS

In addition to the bellows and domes, the expulsion device includes a number of other parts (principally flanges and rings) as identified on the assembly drawing (fig. 2). The majority of these were machined from 304L stainless steel to minimize stress corrosion, even though some of these parts are not directly exposed to liquid fluorine.

Pertinent design features of the two flanges and backup ring that comprise the flanged joint have been described previously, as has the pressure vessel barrel. It is the only major component (other than the bellows) that is not of Type 304L stainless steel. In this case a compromise (Type 304) was made since 304L was not obtainable in the size required, and the barrel is not exposed directly to liquid fluorine. The barrel is machined internally after welding to assure compliance with design tolerances.

The three rings located at the pressurization end of the assembly (adapter, guide, and closure rings) were designed primarily to provide adequate stiffness rather than strength. The important factor is to assure that the rings remain circular even after welding so that adequate clearances will be maintained between the moving and stationary parts. Although detailed dimensioning of the rings is not shown, critical clearances are shown in figure 4.

The helium pressurization/vent line and fluorine fill/discharge line are welded directly to the end domes of the assembly as shown in figure 2. Both lines are made from 1/2-in.- (12.7 mm) diameter 0.035-in. (0.88 mm) wall Type 304 stainless steel tubing, and are fitted with AN tube nuts for convenient connection to other test hardware. Type 304L tubing would have been preferable for the fluorine discharge line, but it was not readily available.

H. FIXTURES

To adequately test the bellows during and after fabrication, two special fixtures were designed and fabricated. One of these is a leak-check fixture required for leak checking the bellows subassembly (bellows plus flange and guide-ring) after the final circumferential welds were made by DK-Aerospace. The other is an exercise fixture that constrains the motion of the bellows in much the same manner as the pressure vessel, but permits visual observation of the bellows exterior.

The conceptual design for the leak-check fixture was developed by Martin Marietta; the final design and fabrication was performed by DK-Aerospace. The fixture consists principally of the following:

- 1) Two large circular end plates that close the ends of the bellows subassembly so that it can be evacuated (through an opening in one of the plates) for a mass-spectrometer leak test;
- 2) Four posts that absorb the external pressure load on the end plates, space the flange and guide-ring so that the bellows is in approximately the compressed condition, and force the guide-ring against the upper end plate by means of lugs;
- 3) Bolts that force the flange against the lower end plate;
- 4) Gaskets that provide an effective seal at both end plates.

Pertinent features of the design are shown in figure 8.

The exercise fixture has the same internal dimensional envelope as the pressure vessel, but is an open structure consisting of two large aluminum rings that are connected by eight stainless steel posts as shown in figure 9. The fixture permits the exterior of the bellows and movable dome to be observed while the bellows is actuated throughout its normal range of travel by alternate pressurization and evacuation of the bellows interior. It can be used to detect binding of sliding surfaces, misalignment tendencies and squirming, to perform bubble leak checks by internally pressurizing the bellows, and to accomplish the cycle proof tests of each bellows assembly in LN₂.

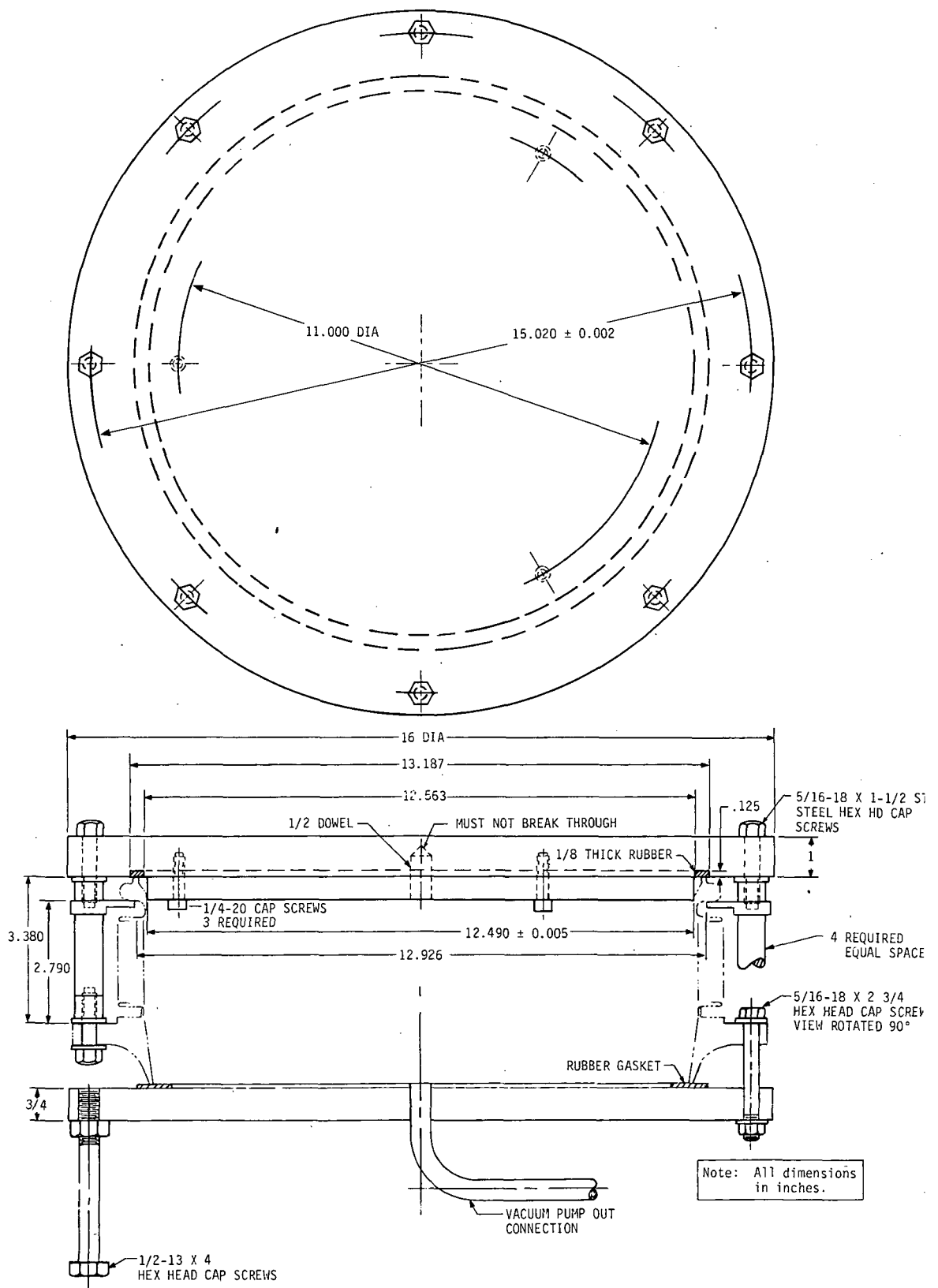
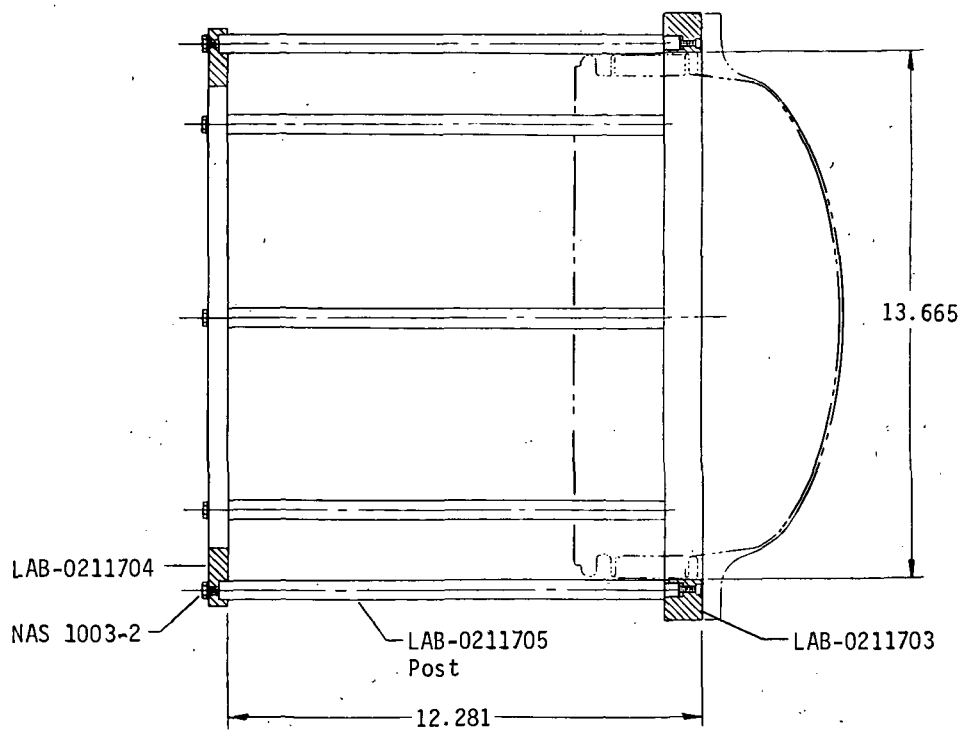


Figure 8 Leak-Check Fixture



Section A-A

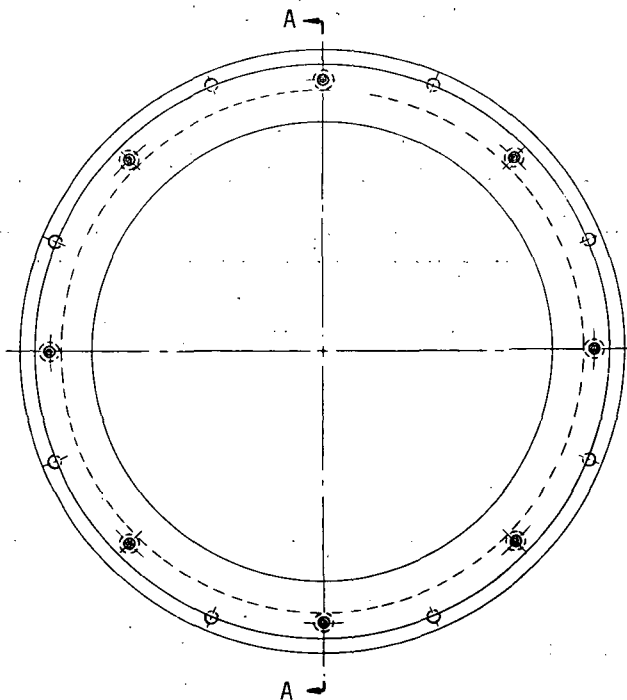


Figure 9 Exercise Fixture

I. FLIGHTWEIGHT EXPULSION DEVICE

In addition to developing the detailed design for the expulsion device to be tested in liquid fluorine, a preliminary design was evolved for an equivalent flight configuration expulsion device. Both designs are based on the same criteria (Sec. A), except that the requirement for a flanged pressure vessel was disregarded for the flight configuration. To permit a direct weight comparison of the two configurations, the same bellows is used in both to provide a displacement of 0.625 cu ft (0.0175 m³). Likewise, both configurations employ the same construction materials (300 series stainless steel).

A preliminary layout of the flight configuration is shown in figure 10. It is very similar to the battleship test article, but differs in the following respects.

- 1) It employs an all-welded construction that eliminates the heavy, and costly, flange joint at the lower end of the assembly.
- 2) It employs a deep upper end dome that supports the movable dome when the bellows is fully extended, thereby providing a negligible ullage volume.
- 3) All material thicknesses are held to a minimum consistent with the performance specifications; i.e., the device is not overdesigned.

A comparative weight breakdown of the test article and the flight article is presented in Table I. Whereas the battleship test article weighs in excess of 100 lb (45 Kg), the flight configuration is estimated to weigh somewhat less than 40 lb (18 Kg). Approximately 50 lb (23 Kg) of this weight reduction is attributable to the elimination of the bolted flanged joint in favor of a simple welded transition section. The remainder of the weight saving is achieved principally through the use of minimum allowable wall thicknesses for the domes, skirts, and barrels.

It should be noted that significant weight reductions are also achievable by changing the L/D (bellows stroke-to-diameter ratio) of the assembly and/or the materials of construction. It is estimated that a change in the L/D from 0.68 to 1.3 would provide a weight saving of at least 20%. A change from 300 series stainless steel to a higher strength alloy such as ARMCO 21-6-9 could provide an additional 20% weight reduction.

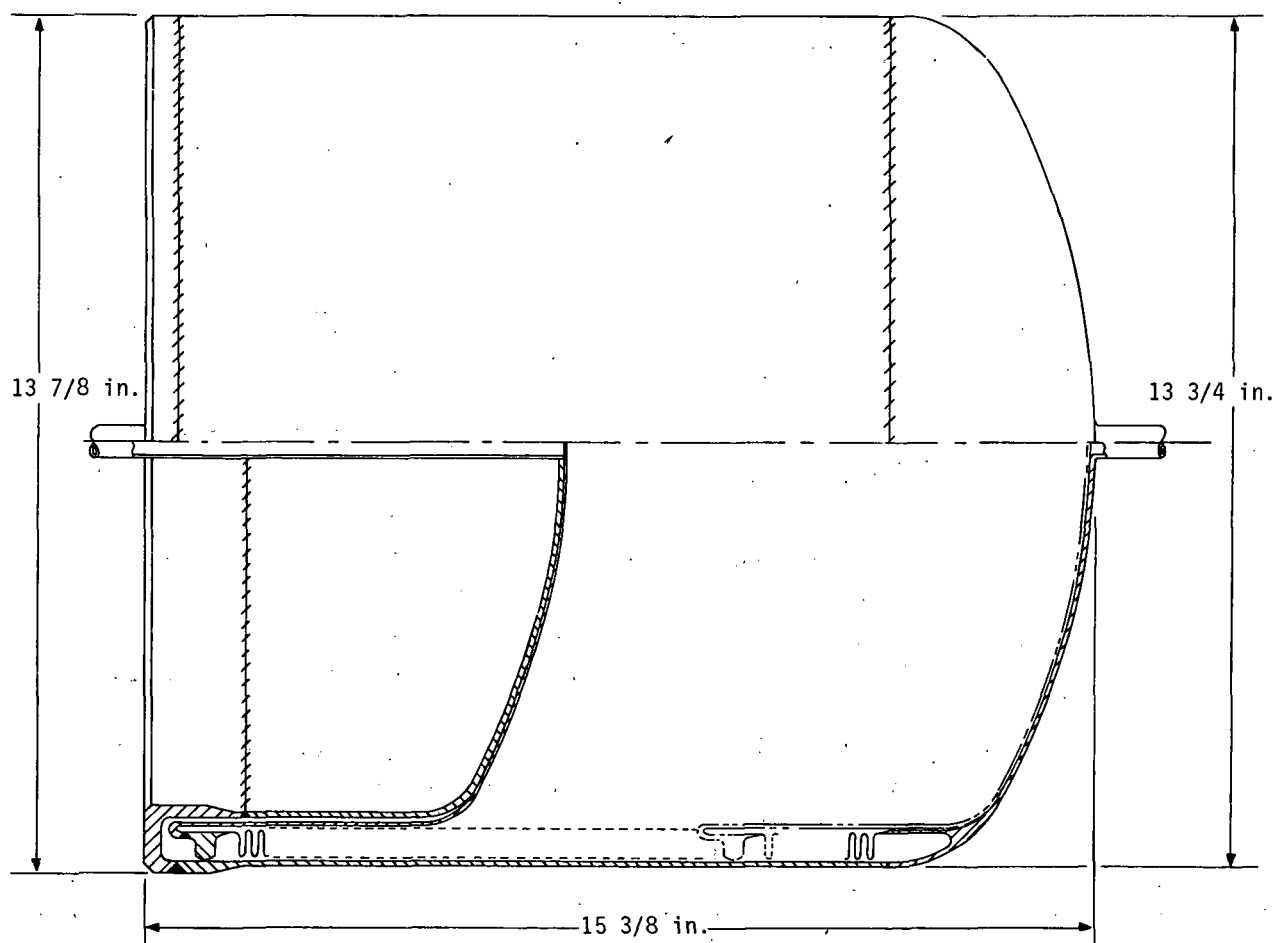


Fig. 10 Flight Weight Expulsion Device

Table I - Expulsion Device Weight Breakdown

Component		Battleship Configuration		Flight Configuration	
		Thickness in. (min)	Weight lb (Kg)	Thickness in. (min)	Weight lb (Lg)
Pressure Vessel	Barrel	.165 (4.20)	21.0 (9.51)	.062 (1.57)	8.0 (3.63)
	Flange		21.0 (9.51)		-- --
	End Ring		6.5 (2.94)		8.0 (3.63)
	Dome	.100 (2.54)	3.0 (1.36)	.080 (2.03)	7.0 (3.17)
	Subtotal		51.5 (23.32)		23.0 (10.43)
Bellows Subassembly	Bellows		3.0 (1.36)		3.0 (1.36)
	Movable Dome	.080 (2.03)	8.5 (3.85)	.040 (1.01)	3.0 (1.36)
	Flange/Joint		14.5 (6.58)		2.5 (1.13)
	End Dome	.100 (2.54)	3.0 (1.36)	.054 (1.37)	4.5 (2.04)
	Rings/Connections		4.0 (1.81)		1.5 (.86)
	Subtotal		33.0 (14.96)		14.5 (6.57)
Miscellaneous	Backup Flange		16.0 (7.25)		-- --
	Nuts/Bolts/Gasket		3.5 (1.59)		-- --
	Subtotal		19.5 (8.84)		
Total Assembly			104.0 (47.12)		37.5 (17.00)

III. FABRICATION TASKS

Final assembly of the expulsion device was accomplished by Martin Marietta, but many of the machining and fabrication subtasks were performed by vendors. A breakdown of the fabrication effort is as follows:

- 1) Parts (flanges, rings and barrels) were machined by a local machine shop in accordance with Martin Marietta design drawings (Assembly drawing LAB-0211633 and associated detailed drawings, see fig. 2);
- 2) Domes were furnished by an outside vendor (Alloys Products Co.) in accordance with Martin Marietta design drawing LAB-0211605 (see fig. 7);
- 3) The bellows were fabricated by DK-Aerospace in accordance with design requirements specified by Martin Marietta, and were welded to end terminals (flanges and rings furnished by Martin Marietta) by DK-Aerospace (see fig. 3);
- 4) Final fitting and welding of the bellows, domes, and other components into complete assemblies was accomplished by Martin Marietta.

The only major fabrication problem encountered was the welding of the bellows to its end terminals. DK-Aerospace experienced no difficulties whatsoever in fabricating the bellows, but they repeatedly failed to produce a leaktight joint between the bellows and the end terminals. Three marginally acceptable bellows assemblies were delivered (out of a total of nine fabricated), but only after numerous tooling and procedural changes had been made. A brief history of the nine bellows is presented in table II; a more detailed discussion of the fabrication tasks is presented in the following paragraphs.

A. PROCUREMENT AND PARTS FABRICATION

Procurement action for all of the major hardware items was completed by August 1969. This included the raw materials (stainless steel plate and pipe) for the flanges, rings and barrels, and the formed stainless steel domes. Three different types of domes are required for the complete assembly, one for the pressure vessel and two for each of the bellows assemblies.

The stainless steel plate and pipe were received in September 1969. Machining of the pressure vessel and other parts was completed the following month. All machined parts were checked and found to satisfy the dimensional tolerances specified by the drawings.

The domes were received in mid-December 1969, and were carefully inspected for conformance with dimensional specifications. The OD of each dome was measured at four locations [45-deg intervals (0.785 radians)], the thickness was measured at four different locations at the skirt end, and the depth was determined. Results are summarized in table III.

TABLE II BELLOWS HISTORY

Serial number	Fabrication and proof test	Cycle test
1	Bellows welded by DK-Aerospace, December 1969, but joints leaked and were irreparable. Unit subsequently subjected to 350 psig (241 N/cm ² , g) hydrostatic test to prove structural integrity of bellows neck and weld joint.	
2	Bellows welded December 1969, but joints leaked and were irreparable. Failure analysis by Martin Marietta in March 1970, including sectioning and metallographic examination of joints, revealed presence of hot short cracks.	
3	Bellows welded January 1970, but joints again leaked and were irreparable. Microscopic inspection by Martin Marietta revealed hot short cracks, three very large leaks. Unit subsequently tested to 300 psig (207 N/cm ² , g) external pressure and 20 psig (13.8 N/cm ² , g) internal pressure to verify structural integrity.	
4	Bellows welded May 1970, but flange leaked adjacent to weld. Unit damaged beyond repair during leak check at DK-Aerospace. Subsequent failure analysis revealed presence of "seams" in the flange material.	
5	Bellows welded May 1970, using new flange material, Type 321 bellows, and improved tooling and procedures. Flange again leaked and guide-ring joint lacked penetration, but repairs were successfully made. Fitting and welding of domes completed by Martin Marietta in July 1970, also hydrostatic testing to 250 psig (172 N/cm ² , g) and cryogenic pressure testing to 265 psig (183 N/cm ² , g). Proof tests completed in August 1970.	300 cycle tests in LN ₂ conducted during September, October, and November 1970. Unit failed (fatigue crack) before 300 cycles. Subsequently used to conduct expulsion efficiency tests in January 1971 after temporary repair of leak.
6	Bellows welded July 1970, but guide-ring joint and flange adjacent to weld. Guide-ring successfully repaired by DK-Aerospace; latter by Martin Marietta. Fitting and welding of domes completed August 1970; six very small leaks adjacent to weld repaired by Martin Marietta. Proof pressure test conducted October 1970; proof testing completed in March 1971.	Subjected to 50 cycle tests in LF ₂ in April 1971 (following 50 cycles of Unit 8). Leaked after 50 cycles and was found to have fatigue crack in bellows longitudinal weld (same as Unit 8).
7	Bellows welded July 1970, but many leaks were present. Judged irreparable.	
8	Bellows welded October 1970, and passed leak check. Subsequent inspection disclosed two small shrinkage cracks in flange weld joint, but these finally judged acceptable. Fitting and welding of domes accomplished January and February 1971; proof testing completed March 1971.	50-cycle tests in LF ₂ conducted in March 1971, resulting in several leaks (fatigue cracks) in bellows longitudinal weld.
9	Bellows welded October 1970, but joints leaked. Unit judged irreparable.	

All nine of the domes are considerably thicker than allowed by design tolerances. In addition, some of the domes are out-of-round and the diameter of the upper dome (-005) is out of tolerance. Since the critical dome diameters are all within tolerance, however, and the thicknesses are out of tolerance on the high side, the domes were judged functionally acceptable. The out of roundness of the movable dome may be corrected by proper fixturing when the dome is welded to the adapter ring. The excessive thickness of the domes results in a device that is capable of withstanding even higher operating pressures than the design values.

B. INITIAL BELLWS FABRICATION

Concurrently with the fabrication of domes and machined parts, DK-Aerospace was proceeding with the tooling required for fabrication and welding of the bellows. The basic tooling for forming and welding the bellows was already in existence and proven, but some tooling modifications were required for fabricating the specific bellows assemblies to be delivered to Martin Marietta. Also, DK-Aerospace fabricated a leak-check fixture to permit leak checking of the bellows subassembly before committing it to final fabrication (fitting and welding of domes). An overall view of the press used to form the bellows convolutions is shown in fig. 11. A finished bellows of a similar design (formed with the same dies, but with a greater number of convolutions) is shown undergoing test in fig. 12.

TABLE III DOME DIMENSIONS (Refer to fig. 7)

Parameter	Specified		Dome 1		Dome 2		Dome 3		Dome 4	
	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Movable domes (-001)										
Outside diameter	12.410 ⁺ .000 - .030	315.21 ⁺ .00 - .76	12.387	314.63	12.394	314.81	12.389	314.68	12.386	314.61
Out of round			0.044	1.12	0.045	1.14	0.042	1.07	0.035	0.89
Thickness	0.080 ± .010	2.03 ± .25	0.106	2.69	0.110	2.80	0.107	2.72	0.108	2.71
Depth (inside)	7.17 ± .03	182.11 ± .76	7.18	182.36	7.16	181.86	7.184	182.48	7.18	182.36
Lower domes (-003)										
Inside diameter	12.00 ± .03	304.80 ± .76	12.000	304.80	12.002	304.85	12.001	304.82	11.998	304.75
Out of round			0.035	0.89	0.015	0.38	0.020	0.51	0.015	0.38
Thickness	0.100 ± .010	2.54 ± .25	0.122	3.10	0.123	3.12	0.121	3.08	0.122	3.10
Depth (inside)	2.78 ± .03	70.61 ± .76	2.795	70.99	2.785	70.74	2.780	70.61	2.785	70.74
Upper dome (-005)										
Inside diameter	12.00 ± .03	304.80 ± .86	12.080	306.82						
Out of round			0.040	1.02						
Thickness	0.100 ± .010	2.54 ± .25	0.128	3.25						
Depth (inside)*	5.90 ± .03	149.86 ± .76	5.895	149.73						
*Depth subsequently changed to 2.63 in. (66.80 mm).										
Note: Tabulated diameters and thicknesses are the average of four readings.										

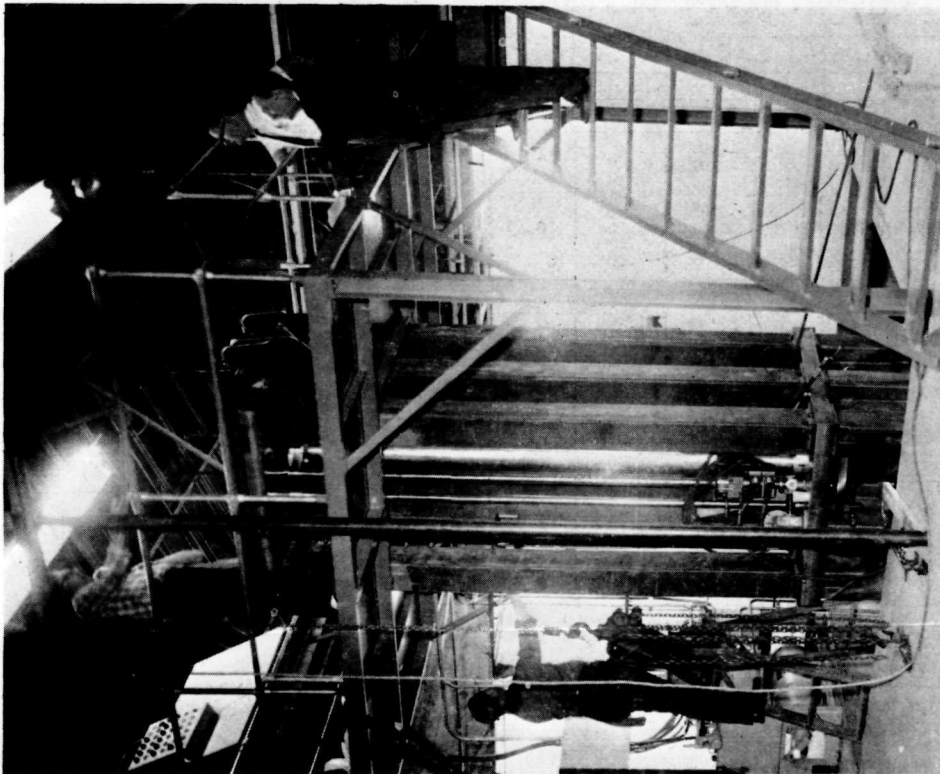


Figure 11 Press Used to Convolute Bellows

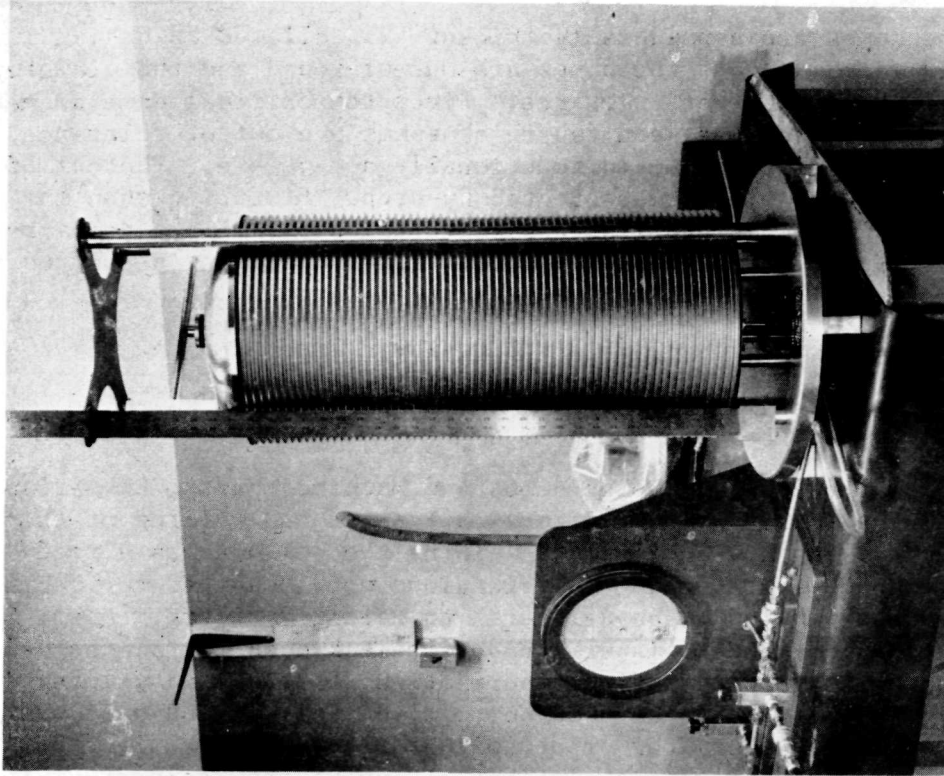


Figure 12 Typical Bellows Undergoing Test

The weld tooling was completed and the first welding of end terminals was accomplished early in December 1969. The first assembly contained a spare bellows fabricated by DK-Aerospace, and two spare end rings furnished by Martin Marietta. The resulting circumferential welds appeared to be excellent, indicating that the joint design, weld tooling, and procedures were satisfactory.

After welding of the first deliverable assembly (fig. 13), a visual inspection indicated that the weld joints were excellent. However, when the assembly was subjected to a leak check, excessive leakage was discovered in the joint between the bellows and the guide. The leak rate was off scale for the mass spectrometer leak detector; the maximum allowable leak rate is 10^{-8} scc He/sec. The bellows assembly installed in the leak-check fixture is shown during leak checking in fig. 14.

Although the cause of the leak was not completely clear, it was decided to proceed with the second assembly. Additional care was taken to assure that parts were clean, and that the tooling was properly set up. The results, however, were the same as before. The weld joints appeared satisfactory, but again an excessive leak was found in the joint between the bellows and guide ring. At this point, an attempt was made to repair the welds on both assemblies, though DK-Aerospace was not optimistic about the probable results. Both machine and hand repairs were attempted, without success.

After the second bellows assembly failed to pass the acceptance leak test, DK-Aerospace conducted a fairly detailed failure analysis of the assembly. It was concluded that the primary problem was excessive workhardening of the bellows lip during the forming operation, which eventually resulted in cracking of the parent metal adjacent to the weld joint. Also, there appeared to be numerous improvements that could be made in the fit of the tooling, and in the associated procedures. Therefore, Martin Marietta agreed that DK-Aerospace should proceed with the welding of the third assembly, after applying appropriate corrective actions. The material used for the rings and flanges was checked and Martin Marietta verified that it is, in fact, 304L stainless steel (certification was provided by the supplier).

The third assembly was welded by DK-Aerospace in January 1970. The weld obtained appeared to be of better quality than previous assemblies, but it also leaked.

C. FAILURE ANALYSIS AND CORRECTIVE ACTIONS

As a result of the three consecutive failures experienced by DK-Aerospace in welding the bellows to the end terminals, Martin Marietta ordered fabrication to cease until a detailed evaluation of the failures could be made and appropriate corrective actions identified. Accordingly, bellows assemblies 2 and 3 were shipped to Martin Marietta and subjected to a comprehensive failure analysis. The major results of this failure analysis were as follows:

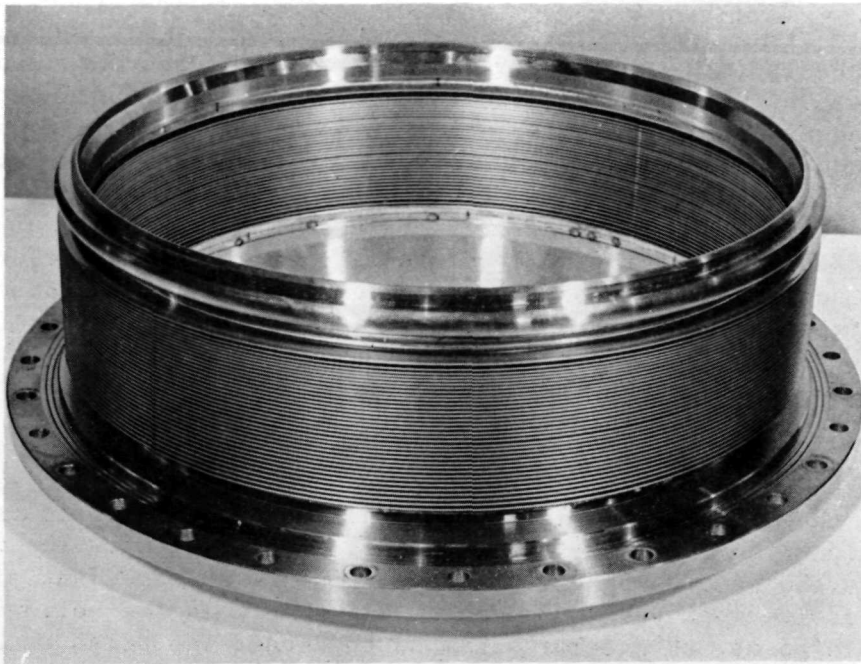


Figure 13 Bellows Subassembly as Received from DK-Aerospace

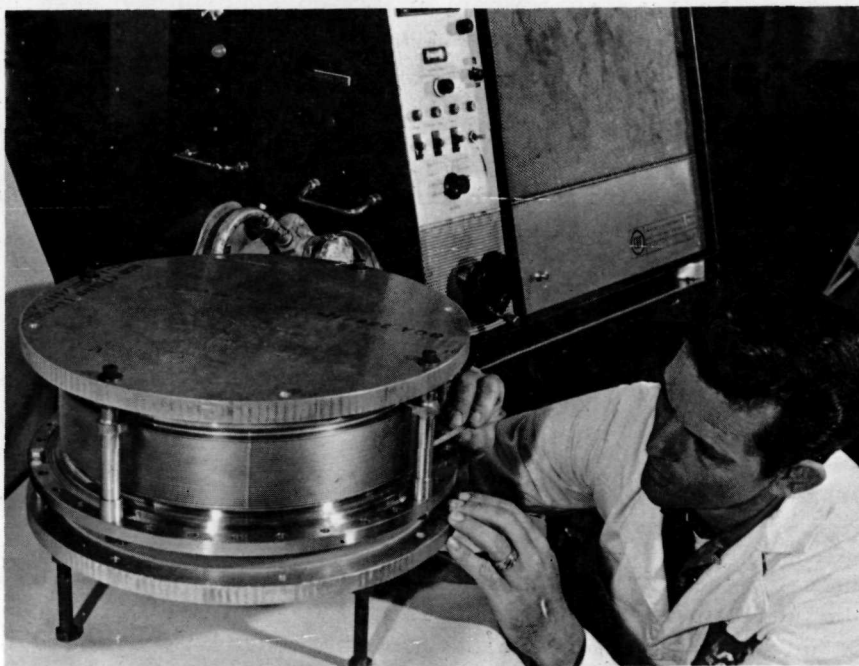


Figure 14 Bellows Subassembly Being Leak Checked

- 1) The general quality of the weld joints (determined from microscopic inspection, sectioning and metallography examination, and leak checking) showed a continuing improvement from the "practice" assembly through assembly 3, but it still left a great deal to be desired. The joints were only of mediocre quality, and were not repeatable, probably because of tooling and/or procedural deficiencies. A specific example of a region of very poor weld penetration found in assembly 2 is shown in fig. 15;
- 2) The major cause of the weld failures was "hot short cracking" of the bellows end tube adjacent to the weld bead. These cracks were identified in photomicrographs of sections cut from assembly, and also microscopic examination of assembly 3, once the leak regions had been pinpointed. A specific example of one of these cracks is shown in fig. 16, a photomicrograph of the bellows parent material adjacent to the weld bead on assembly 2. The depth of the crack at this section is ~ 0.003 in. (0.08 mm), nearly one-half the total material thickness. At other locations the crack undoubtedly penetrates all the way through as evidenced by the excessive bellows leak rate that was measured during the acceptance test. These cracks cannot be identified in any of the X-rays that were obtained;
- 3) The Type 347 stainless steel sheet used to fabricate the bellows did not satisfy NAA Specification RB 0170-103, and therefore, is subject to "hot short cracking" as a result of welding. The chemical analysis of bellows 2 as determined by the Martin Marietta Quality Laboratory is as follows:

<u>Constituent</u>	<u>Percentage</u>
C	0.06
Mn	1.30
Si	0.48
Ni	10.1
Cr	17.2
Mo	0.19
Cb	0.62

From the above, the nickel equivalent is:

$$\text{Ni equiv} = \text{Ni} + 30\text{C} + 0.5 \text{ Mn} = 12.55\%,$$

and the chromium equivalent is:

$$\begin{aligned} \text{Cr equiv} &= \text{Cr} + \text{Mo} + 1.5 \text{ Si} + 0.5 \text{ Cb} \\ &= 18.42\%. \end{aligned}$$

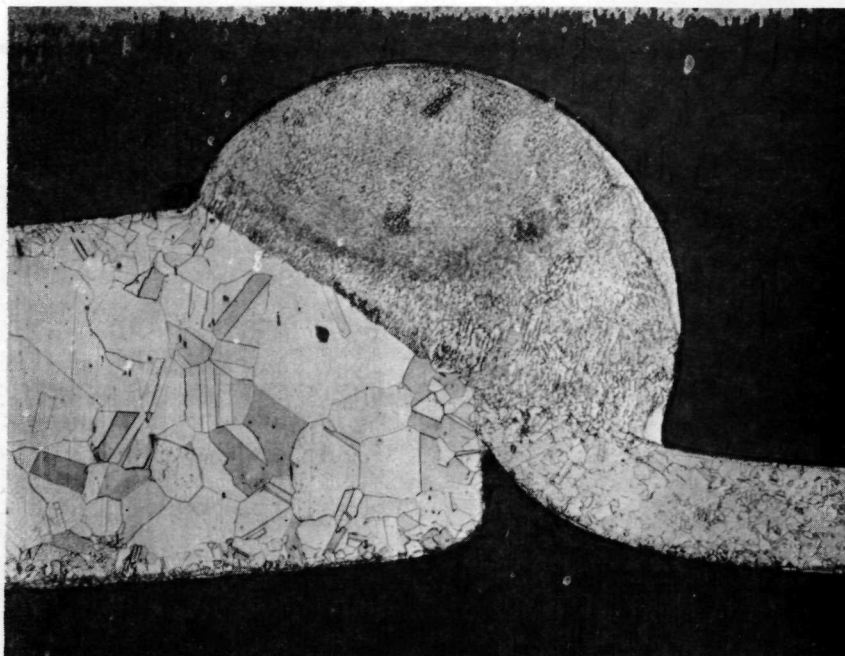


Figure 15 Region of Poor Weld Penetration,
Bellows Assembly 2

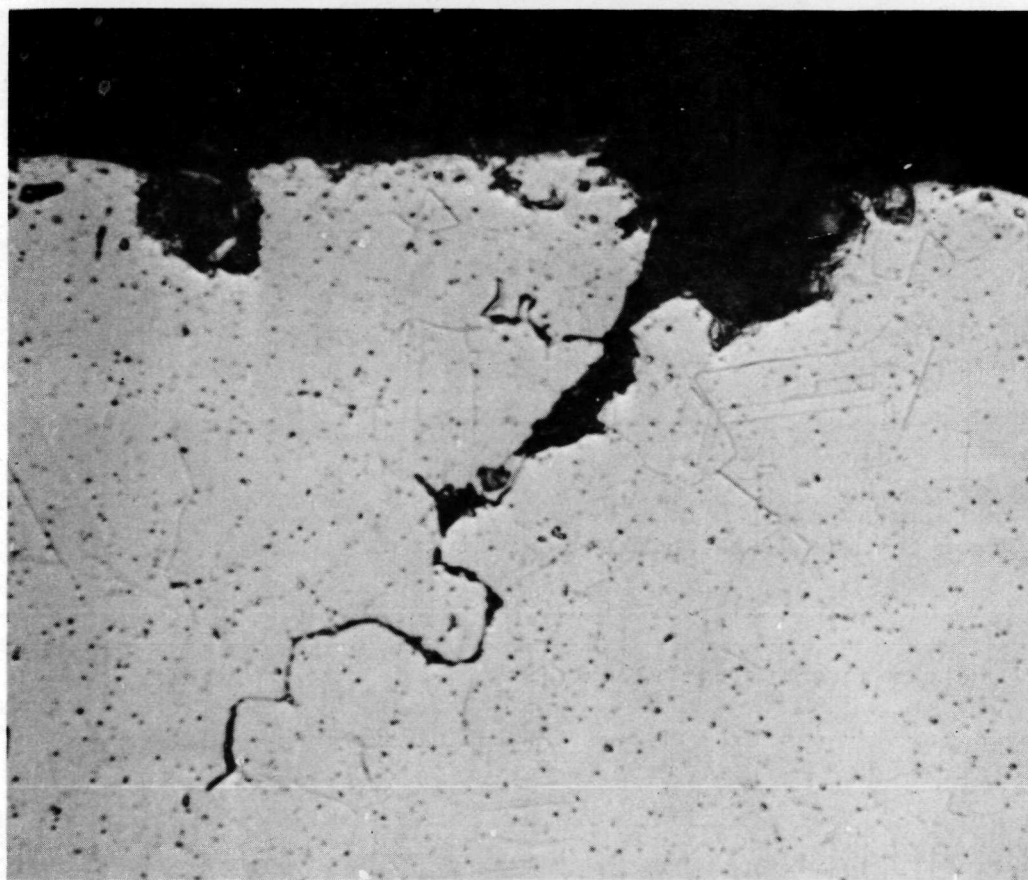


Figure 16 Crack in Bellows Adjacent to Weld Bead,
Bellows Assembly 2

The NAA specification requires that the chromium equivalent must be:

$$\text{Cr equiv} \geq 0.92 \text{ Ni equiv} + 8.00$$

$$\geq 19.65\%.$$

Because the material did not meet the NAA specification does not mean that it is impossible to obtain satisfactory welds; however, the probability of cracks occurring is relatively high;

- 4) A careful leak check of assembly 3, using "Duxseal" to incrementally isolate various regions of the weld joints, disclosed three large leaks, each of sufficient magnitude to produce an off-scale reading ($>10^{-3}$ scc He/sec) of the leak detector. One of these was found in the joint between the bellows and the large flange, the other two were in the joint between the bellows and guide ring.

Based on the foregoing data and further discussions with DK-Aerospace, the following corrective measures were adopted for fabrication of additional bellows assemblies:

- 1) Type 321 stainless steel would be used instead of Type 347 to preclude the formation of hot short cracks during welding;
- 2) New external backing rings would be provided to assure a better clamping pressure on the bellows during welding. The rings would be made of a stronger alloy (RW Class 3 copper), and tapered internally. They would not be segmented, however, as proposed by Martin Marietta;
- 3) Future assemblies would be processed on an engineering work order rather than a production order, thereby permitting much closer control of all processing. The project engineer would be personally responsible, and the most qualified personnel would be used throughout all phases of forming, trimming, and welding;
- 4) Process procedures would be prepared in greater detail as recommended by Martin Marietta;
- 5) Additional practice welding would be accomplished as required, using rings remachined from existing assemblies.

D. WELDING OF BELLWS 4 AND 5

The corrective actions were completed by DK-Aerospace in approximately two months. By late April 1970 six new bellows had been fabricated of Type 321 stainless steel, the proposed tooling modifications had been made, and additional practice welding had been accomplished. Bellows assembly 4 was then welded, but it failed to pass the leak check as a result of a number of leaks at the flange-end weld. Isolation of the leaks, however, disclosed that they were through the flange material adjacent to the weld bead, not through the weld bead or the bellows material. Suitable repairs could have been made, but the bellows assembly was irreparably damaged by DK-Aerospace as a result of procedural error during leak check. The assembly had been installed in the leak check fixture and left overnight in the evacuated condition. One of the spacers that was used to separate the two end plates of the fixture either failed completely or slipped out of position, resulting in collapse of the assembly and extensive damage to the bellows.

To further investigate the leaks in the flange parent material, the thin weld ring was cut off the flange, sectioned, and subjected to metallographic examination by Martin Marietta. A typical result is shown in fig. 17, a cross section of the ring at 2000X magnification. The crevice may be identified as a "seam" (a void that was rolled into the plate material) that extends nearly two-thirds through the thin weld ring at this particular cross section. This type of flaw occurs occasionally in heavy plate material, but would not ordinarily be expected to occur in the small number of parts involved in this program.

Concurrent with the assembly of bellows assembly 4, fabrication of assembly 5 proceeded. A new flange was machined from additional material previously furnished by Martin Marietta, and a new guide-ring was machined from the flange of assembly 3. The bellows was welded in May 1970, but again the assembly was found to leak through the flange material, much the same as assembly 4. Two specific leaks were identified by leak check and by dye check. These were successfully repaired by Martin Marietta personnel, using a simple internal chill bar to dissipate excess heat.

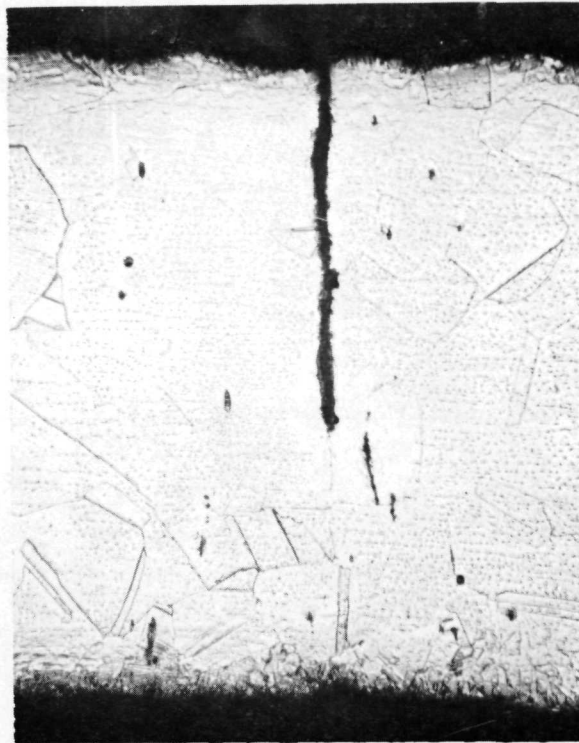


Figure 17 Seam in Flange, Bellows Assembly 4

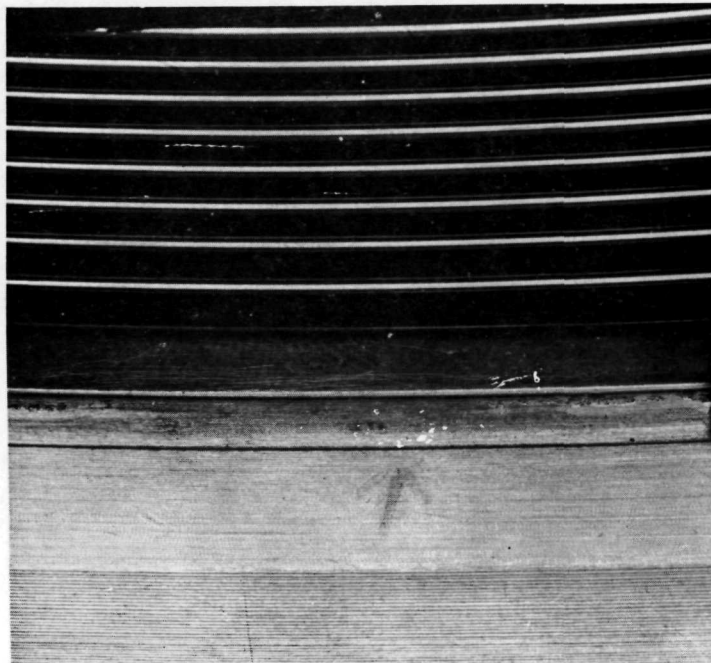


Figure 18 Unacceptable Guide Ring Weld, Bellows Assembly 5

Although assembly 5 did not leak after the flange had been repaired, the weld at the guide-ring end was found to be unacceptable because of inadequate penetration (fig. 18). DK-Aerospace was reluctant to attempt a repair, but Martin Marietta insisted that this be done to preclude possibility of a structural failure of the weld. The first attempt to repair the weld was unsuccessful, but a second weld bead was successful. The assembly was leak checked at DK-Aerospace and subsequently at Martin Marietta, without evidence of any leakage whatsoever. It became the first assembly of five to be acceptable for further fabrication, i.e., the fitting and welding of the end domes.

E. WELDING OF BELLOWS 6 AND 7

Flanges and rings for assemblies 6 and 7 were machined by DK-Aerospace during June 1970. The flanges were machined from new material previously furnished by Martin Marietta, the guide rings were machined from the flanges recovered from assemblies 1 and 2.

Assemblies 6 and 7 were welded the following month. Several small leaks were found in assembly 6 on the bellows side of the weld on the guide-ring end. These leaks were successfully repaired by running a new bead for approximately 3 in. (7.6 cm) in the region of the leaks. DK-Aerospace also identified one small leak ($\sim 10^{-6}$ scc He/sec) in the flange [~ 0.040 in. (1.02 mm) from the weld bead], but this leak could not be located in a subsequent leak check by Martin Marietta. Bellows 6 then became the second unit (of six) to be acceptable for further fabrication.

Bellows 7 was found to have a number of leaks on both sides of the weld beads. An attempt was made to repair it, but this was unsuccessful. Therefore, this unit became the fifth of seven to be rejected.

F. BELLOWS 8 AND 9

Because of the repeated failures that had been encountered in the weld joints, DK-Aerospace desired to conclude their portion of the program with the delivery of only two bellows (assemblies 5 and 6), but agreed to attempt fabrication of two more assemblies. These assemblies would employ flanges and rings machined from forgings rather than plate material to minimize the possibility of inclusions or voids in the raw material. Only one of the assemblies would be required to accomplish the proposed cycle test program. The other would serve as a spare if indeed both were good (leaktight) units.

These two assemblies (8 and 9) were welded late in October 1970. Bellows 8 passed the leak check the first time (without repairs), and was immediately shipped to Martin Marietta. Subsequent review of the weld X-rays showed that one or more small cracks was present in one of the welds, so the weld was carefully inspected with a stereomicroscope. Two small shrinkage cracks were identified approximately $\frac{1}{2}$ in. (1.27 cm) apart. Both cracks were in the weld adjacent to the bellows neck, but did not extend into the parent metal. They appeared only on the outside surface of the weld. There was no evidence of a crack on the inner surface where it would be especially critical in the presence of fluorine.

To further investigate the integrity of the joint, the assembly was carefully cleaned (using lox cleaning procedures) to remove any foreign matter that might be plugging the crack, and then leak-checked with a standard mass spectrometer leak detector. No measurable leakage could be detected; i.e., leakage was less than 10^{-8} scc He/sec.

As a result of the foregoing, and further consideration of the very low stress levels likely to be experienced in the joint, it was concluded that the assembly is acceptable for use in the proposed fluorine tests. The cracks could possibly propagate, but the growth rate would be very low. It was considered almost inconceivable that the crack could produce a catastrophic failure of the assembly, and very unlikely that the crack would penetrate the inner surface of the joint and produce a measurable leak prior to failure of the bellows in the high stress regions of the convolution crests and roots. This became the third assembly (of eight) to be accepted for further fabrication.

Bellows 9 did not pass the leak check. It was judged irreparable (by DK-Aerospace), so was rejected for further consideration in the program. Since this unit would have served only as a spare, the planned test program could be successfully completed without it. It was very disturbing, however, that the percentage of good weld joints produced by DK-Aerospace remained so low.

G. FITTING AND WELDING OF DOMES

Completion of all three bellows assemblies (5, 6, and 8) by Martin Marietta followed the same basic procedures, although they were conducted at different times over a period of several months. The major steps in the fabrication sequence were as follows:

- 1) Each bellows subassembly was fitted to the exercise fixture to check the diameter of the shoulder [13.865 in. (352.17 mm)] on the flange. The fit was satisfactory, indicating that the shoulder was within tolerance. The inside diameter of the flange was checked with a micrometer caliper and found to be within tolerance [12.028 in. (305.51 mm)].
- 2) The clearance between the tapered section of the movable dome and the flange was determined by fitting these parts with the end dome. The tapered section of the flange was seated on the movable dome, then the end dome was set on the movable dome as shown in fig. 19. The average clearance between the flange and the end dome (measured at four locations) was 0.100 in. (2.54 mm) for assembly 5. This corresponds to a radial clearance of ~ 0.017 in. (0.43 mm) at the 10 deg (0.175 radians) tapered section when the end dome is butted up against the flange, an adequate clearance for the expulsion device. Results obtained for the other two assemblies were similar.
- 3) A preliminary fit of each assembly was made so that the effects of weld distortion could be quantitatively determined. First, the bellows was compressed to the proper length using the aluminum ring and bolts as shown in fig. 19. The bellows was compressed until the span of 32 convolutions, measured with dividers on the inside diameter of the bellows, was exactly 1.60 in. (406. mm), i.e., 0.050 in. (1.27 mm) per convolution. Then the bellows subassembly was set on the end dome, the movable dome inserted, and the axial distance between the end of the movable dome and the end of the guide-ring measured with the aid of a flat bar and micrometer caliper. This distance, the average of four measurements, was found to be in the range of 0.200 in. (5.08 mm) to 0.215 in. (5.46 mm) for the three assemblies (see fig. 20).
- 4) The $\frac{1}{2}$ -in. (1.27 cm) diameter inlet/outlet port was drilled in the center of the end dome.
- 5) The end dome was then welded to the bellows flange. Both pieces were first chamfered at a 45-deg angle (0.786 radians) to a depth of ~ 0.070 in. (1.78 mm), then centered and tack welded (employing an argon purge), and finally TIG welded around the entire circumference from the outside. During welding the bellows was held in the compressed condition (with the aid of the aluminum ring and several bolts) to permit more convenient handling and to minimize the possibility of damage. Following welding, it was necessary to grind a portion of the interior of the flange to compensate for a slight diametral shrinkage of flange during welding.
- 6) The fit of the assembly was rechecked in the same manner as before (Step 3 above). This time the axial distance between the end of the movable dome and the end of the guide ring was found to be only 0.150 in. (3.81 mm) to 0.156 in. (3.96 mm), indicating an effective axial shrinkage of nearly 1/16 in. (1.6 mm) as a result of welding.

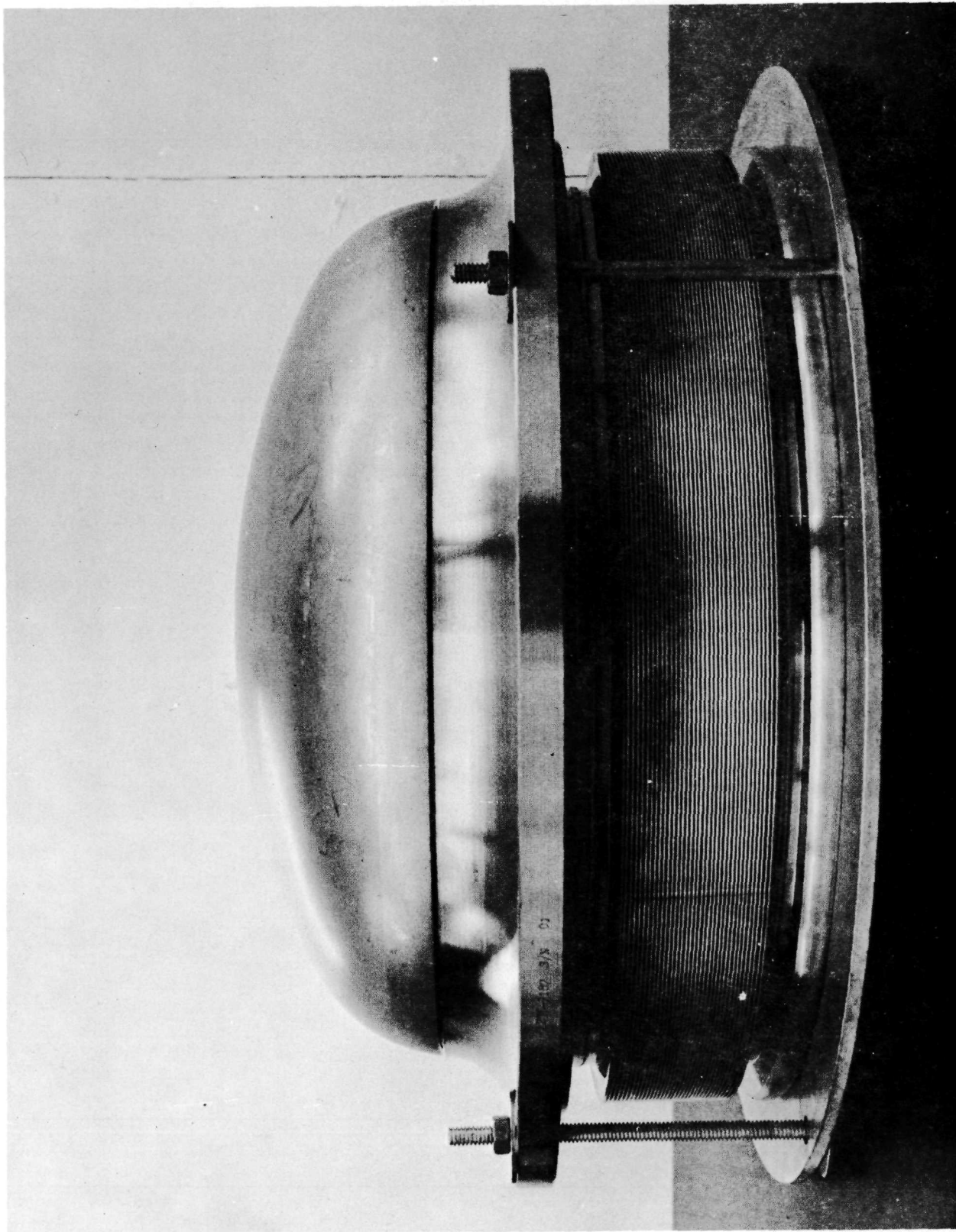


Figure 19 Dome Fit on Bellows Assembly 8

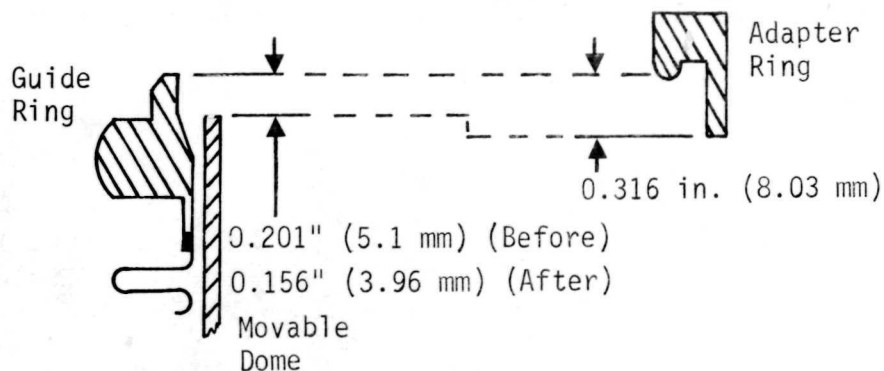


Figure 20 - Fit of Movable Dome, Assembly 6

- 7) The length of the neck on the guide ring was 0.316 in. (8.03 mm) for all the assemblies (fig. 20). The difference between this value and 0.156 in. (3.96 mm) (for assembly 6) represents the interference between the parts that is eliminated by final machining of the adapter ring. To provide a slight margin of safety (adequate length for the compressed bellows), only 0.145 in. (3.68 mm) was machined from the adapter ring instead of 0.160 in. (4.06 mm), leaving a total adapter length of 0.485 in. (12.3 mm) for assembly 6. The corresponding values for the other two assemblies were very similar.
- 8) The diameter of the shoulder on the flange was rechecked after welding, again using the exercise fixture as a go/no-go gage (Step 1, above). A slight interference was found on the shoulder outside diameter, presumably the result of welding on the end dome. This was corrected by chucking the flange in a lathe and turning down the shoulder a slight amount.
- 9) The adapter ring was welded to the movable dome. The dome end was first chamfered, then centered and tack welded, and finally TIG welded around the entire circumference using an argon purge. An aluminum fixture was used to support the inside of the adapter ring and minimize distortion due to welding, as shown in fig. 21.
- 10) The $\frac{1}{2}$ -in. (1.27-cm) diameter fluorine inlet/outlet tube was welded to the end dome (from the inside) employing an argon purge.
- 11) The two subassemblies were cleaned for fluorine service at the Cold Flow facility in accordance with Martin Marietta Process Specification EPS 50405. The subassembly is cleaned before making the final closure weld because this is the last time that the interior of the bellows is accessible. To increase the accessibility of the interior of the convolutions, the bellows was extended approximately 6 in. (15.2 cm) using the aluminum ring, the four posts and lugs from the leak check fixture, and four long 5/16 in. (8 mm) threaded rods as shown in fig. 22. The movable dome (and attached adapter ring) required no special fixturing for cleaning.



Figure 21 Movable Dome Ready for Welding to Adapter Ring



Figure 22 Bellows Assembly 8 Ready for Cleaning

- 12) The final closure weld, (a TIG weld of the guide ring to the adapter ring) was made after receipt of the parts from cleaning. First, the plastic bag containing the bellows subassembly was cut open sufficiently to permit an argon purge tube to be inserted through the inlet/outlet fitting. The purge was continued for several minutes to purge all the air out of the bag. Next the movable dome was quickly inserted into the bellows, through suitable split openings in the two plastic bags. The argon purge was continued overnight to assure that all air was removed from the interior of the assembly. Finally, the sub-assemblies were aligned, tack welded, and then TIG welded around the entire circumference, again using the aluminum fixture shown in fig. 21.
- 13) Upon completion of welding, the assembly was subjected to a final leak check by evacuating the bellows interior with the CEC leak detector, and directing helium at the weld regions. Assemblies 5 and 6 both exhibited one or more small leaks in the flange material adjacent to the weld bead. It is not known whether these leaks were caused by the welding on the domes, or were those leaks temporarily plugged by dye or Duxseal. In any case, they were judged reparable. Each leak was carefully isolated, then repaired by a manual weld, and again leak checked. The repairs proved successful. Assembly 8 exhibited no leaks whatsoever.
- 14) The final step in the fabrication procedure was the X-ray of the three circumferential welds on each assembly by the Martin Marietta Quality Control Laboratory. In preparation for X-raying, the fluorine inlet/outlet line was fitted with a hand valve, the bellows evacuated to seat the movable dome tightly into the end dome, and the valve closed. Each weld was X-rayed in eight sections. All welds were satisfactory.

IV. BELLWS PROOF TEST

Upon completion of fabrication, each bellows assembly was subjected to a proof test consisting of:

- 1) A proof pressure test to 265 psig (183 N/cm^2 , g)(proof factor of 1.75) at LN_2 temperature, followed by a leak check;
- 2) Five complete cycles at LN_2 temperature, followed by a second leak check.

Only three bellows assemblies (5, 6, and 8) reached the stage of proof testing. Because of the erratic delivery schedule, testing of these assemblies was spread out over a lengthy time period, e.g., proofing of assembly 5 was initiated in July 1970, proofing of 8 was not completed until March 1971.

In addition to the planned proof tests, several design confirmation tests were conducted to prove the structural integrity of the bellows under design pressure loads. Two of the early assemblies that exhibited leaky welds, but that were structurally sound, were used for these tests.

A. DESIGN CONFIRMATION TESTS

As a result of the long delay in receiving the first acceptable bellows from DK-Aerospace, adequate time was available to conduct several special tests to prove the structural integrity of the bellows, including the joint at the end terminals. To perform these special tests, the leak-check fixture was used to seal the ends of the bellows subassembly (bellows welded to end terminals) so that it could be subjected to high external pressures while rigidly held in the compressed configuration, or subjected to low internal pressures while held in the extended position. The external pressure tests were conducted by installing the bellows assembly in the leak-check fixture as shown in fig. 23, then placing the entire assembly inside a large pressure vessel and subjecting it to the desired pressure levels. A short section of 6 in. (15.2 cm) pipe installed inside the bellows and clamped between the two end plates of the fixture absorbed the axial pressure load and held the bellows at its normal compressed length. Tissue paper strips were taped across the bellows convolutions to provide evidence of any tendency for the convolutions to flare out under the influence of the pressure load.

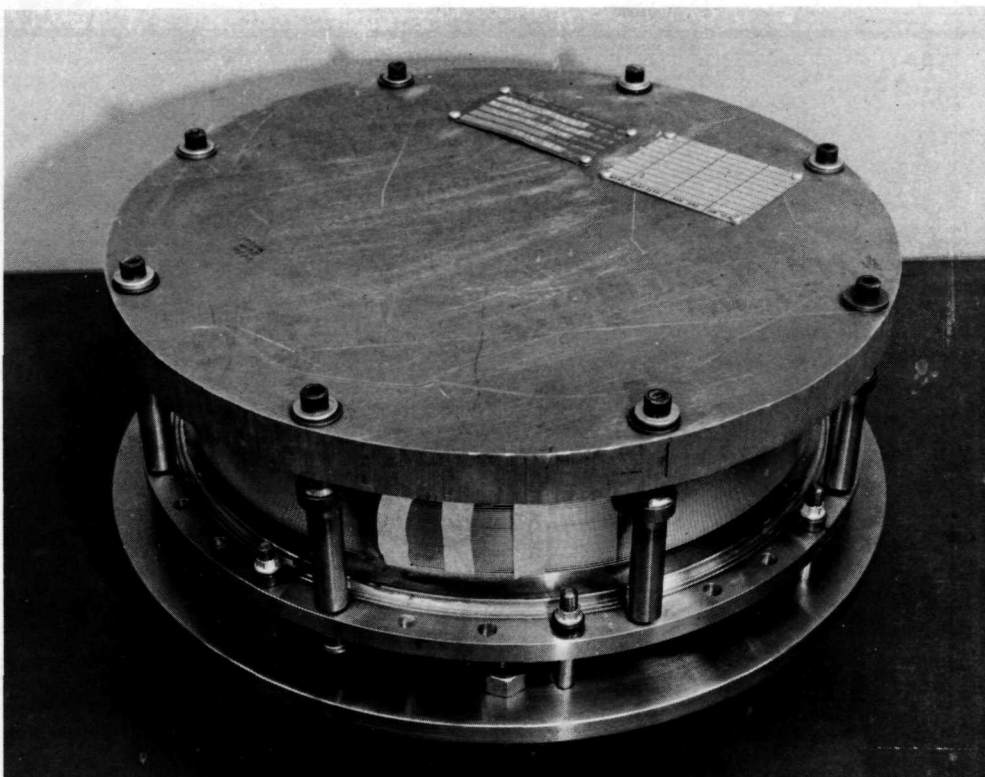


Figure 23 Bellows Assembly Installed in Fixture for Pressure Test

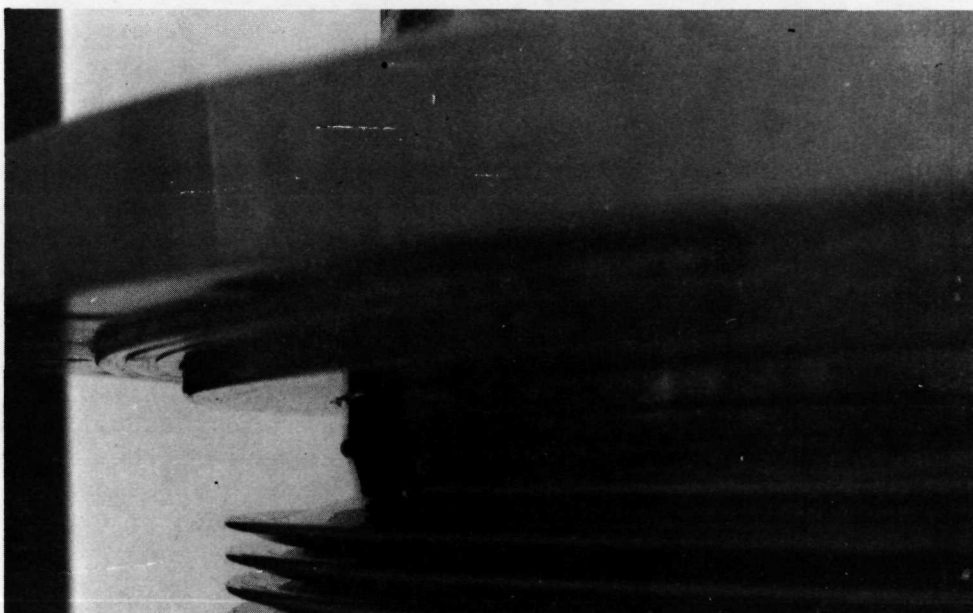


Figure 24 Closeup Showing Distorted Bellows Neck

Bellows 2 was tested first, with the test pressure applied in 50 psig (34.5 N/cm^2 , g) increments up to 200 psig (138 N/cm^2 , g), and 25 psig (17.2 N/cm^2 , g) increments from 200 to 300 psig (138 to 207 N/cm^2 , g). A visual inspection for damage was made at each pressure increment. This inspection required that the pressure vessel be vented, the manhole cover removed, and the bellows assembly withdrawn for inspection. No actual damage was detected, but the bellows neck was deformed slightly from its initial configuration, as shown in fig. 24. The neck did not buckle however, and showed no signs of impending failure. None of the tissue paper strips were torn.

Subsequently, bellows 1 was tested in a similar manner, but to an even higher pressure. It was subjected to 350 psig (241 N/cm^2 , g) with no adverse effects other than distortion of the bellow necks. Since the normal proof pressure is only 265 psig (183 N/cm^2 , g), it was concluded that there is little danger that the bellows neck will buckle.

In addition to the external pressure test, bellows 3 was subjected to an internal pressure test (in the extended position) to determine its squirm characteristics. Again the leak-check fixture was employed to seal the ends of the assembly; eight extension rods were used to absorb the pressure load and retain the bellows at its normal extended length as shown in fig. 25.

To minimize hazards, this test was conducted as a hydrostatic test by filling the bellows with water and then gradually pressurizing it until the first indication of squirm was noticed. This finally occurred at a pressure of 20 psig (13.8 N/cm^2 , g), a value somewhat higher than the 16 psig (11 N/cm^2 , g) predicted by DK-Aerospace. This further increased our confidence in the ability of the bellows to perform satisfactorily under design load conditions.

B. HYDROSTATIC TESTS, BELLWS 5

Before conducting the planned proof tests of the first bellows assembly (No. 5) in LN_2 , the assembly was subjected to hydrostatic pressure tests to further confirm the adequacy of the bellows design. The first hydrostatic test of assembly 5 was conducted late in July 1970 immediately after the final fabrication tasks were completed. The test was accomplished as follows:

- 1) The bellows assembly was installed in the pressure vessel and the 32 bolts torqued to 160 in.-lb (18.1 N-m);
- 2) A small hand valve was installed in the pressurization line to control the flow in and out of the assembly, then the assembly was evacuated (bellows extended) through a flex line to remove all traces of air;

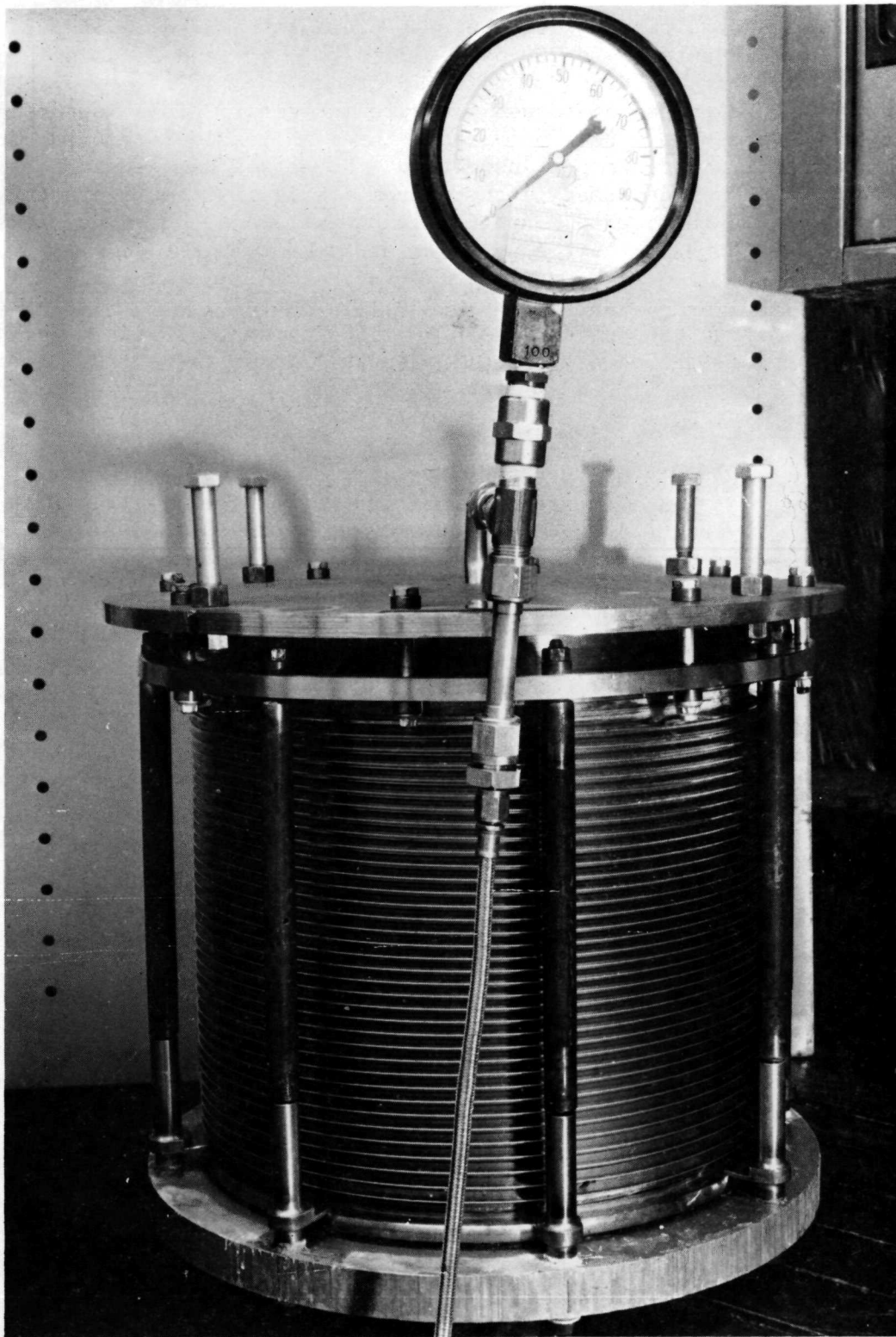


Figure 25 Bellows Assembly in Fixture for Squirm Test

- 3) The assembly was filled with deionized water by first priming the flex line and inserting it into a 5-gallon (0.019 m^3) container of deionized water, opening the hand valve to initiate flow, and finally evacuating the fluorine inlet/outlet line to fully compress the bellows and fill the entire pressurization volume with water. Approximately 7.5 gallons (0.0284 m^3) of water was required;
- 4) The assembly was gradually pressurized to 150 psig (103 N/cm^2 , g) through the flex line with gaseous nitrogen. Careful inspection revealed no evidence of leakage after a 5-minute (300 sec) hold period;
- 5) The pressure was gradually increased to 200 psig (138 N/cm^2 , g) and held for a period of 10 minutes (600 sec). Again there was no evidence of leakage;
- 6) The test was concluded by venting the nitrogen pressure, then returning the majority of the water to the container through the pressurization line by slightly pressurizing the interior of the bellows with helium through the fluorine inlet/outlet line. The remaining water in the "ullage volume" was drained out when the assembly was disassembled at the flange joint;
- 7) After disassembly, the bellows was carefully inspected for damage, but no discrepancies were noted.

A second hydrostatic test was conducted in the same manner as described above, except that a test pressure of 250 psig (172 N/cm^2 , g) was used. No leaks were evident during the test; no damage was observed following the test, but the bellows neck had deformed slightly. Subsequently the bellows assembly was baked overnight at a temperature of 250°F (394°K) to remove all traces of water.

A "reverse" leak check of the assembly was then conducted by installing it in the pressure vessel and evacuating the pressurization side of the bellows through the CEC leak detector. Application of helium to the exterior welds of the assembly disclosed no leaks, but purging of helium into the bellows interior revealed a $\sim 10^{-6}$ scc He/sec leak. The bellows was removed from the assembly, then leak checked in the opposite direction (by evacuating the fluorine-side of the bellows) to pinpoint the leak location. The leak was found to be in the same general region as the previously repaired leak, i.e., in the flange adjacent to the weld. It was repaired by a manual weld in the same manner as before. A subsequent leak check revealed no leakage whatsoever.

C. DISPLACEMENT TEST, BELLOWS 5

Assembly 5 was also subjected to a simple displacement test before the planned proof tests. For this test, the bellows assembly was cycled at ambient temperature several times to observe its operation for any evidence of abnormalities, and to determine its critical operating pressures, i.e., displacement versus pressure characteristics.

First, the bellows assembly was installed in the exercise fixture, fitted with a scale to measure the position of the movable dome, and attached to a pressure/vacuum source through the inlet/outlet line (fig. 26). Then the bellows was compressed in small increments by gradually evacuating the assembly until it was fully compressed (movable dome seated). Pressure and displacement readings were taken at each increment. Next the bellows was extended in small increments by first bleeding helium into the inlet/outlet port until ambient pressure was reached, then pressurizing with helium in small increments until the bellows was fully extended. Readings were again taken at each increment. Finally, the bellows was returned to its relaxed position by gradually venting the helium pressure back to ambient, again taking a series of readings. The entire procedure was then repeated to confirm the results. No anomalies were observed.

The resultant displacement data are shown in fig. 27. Due to the fact that the bellows is stressed beyond yield during cycling, it exhibits a small hysteresis loop, but the effective "spring-rate" is approximately the same during compression as extension. The pressure differential required to move the bellows from the relaxed position to either extreme of travel is approximately 1 psi (0.68 N/cm^2), and the free length following extension is nearly 2 in. (5 cm) greater than that following compression.

D. PRESSURE TEST, BELLOWS 5, 6, AND 8

The pressure tests of the three bellows assemblies in LN_2 were spread over a period of many months, but the procedures were very similar for all three. Assembly 5 was pressure tested late in July 1970, as follows:

- 1) The bellows assembly was installed in the pressure vessel, and the flange bolts torqued to 160 in.-lb (18.1 N-m);
- 2) The assembly was then installed in an insulated open-mouthed container and connected to controllable gas supplies. Regulated helium was attached to the bellows inlet/outlet line, and a nitrogen supply was connected to the pressurization line (fig. 28);
- 3) The assembly was purged of air (three cycles) by alternately pressurizing and venting opposite sides of the bellows to $\sim 2 \text{ psig}$ (1.4 N/cm^2 , g), a pressure sufficient to assure full displacement of the movable dome;
- 4) The insulated container was gradually filled with LN_2 , bringing the bellows assembly down to LN_2 temperature;
- 5) The gas side of the bellows was then filled with LN_2 to as high a level as possible, using a small 100 liter (0.1 m^3) dewar;

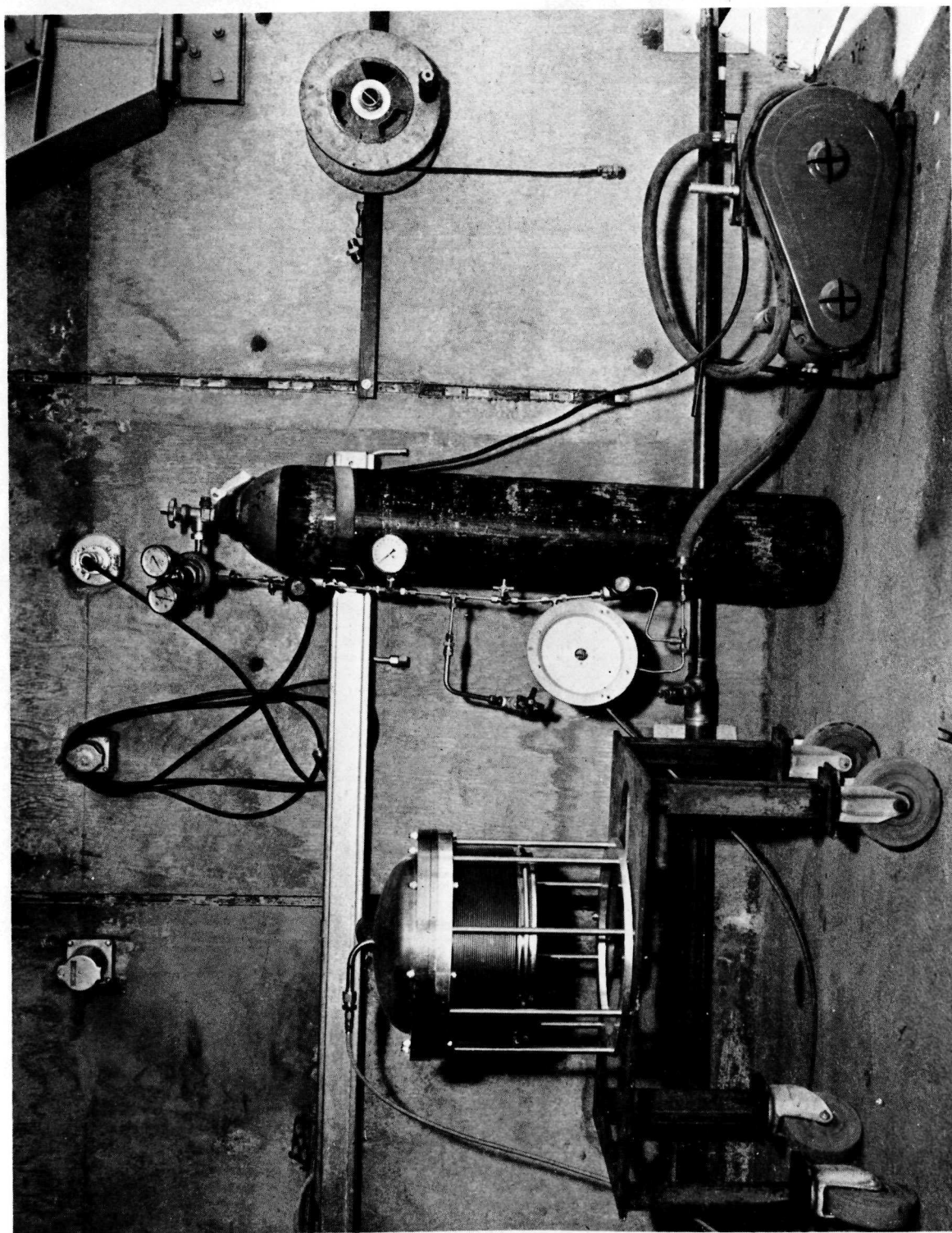


Figure 26 Test Apparatus for Bellows Displacement Test

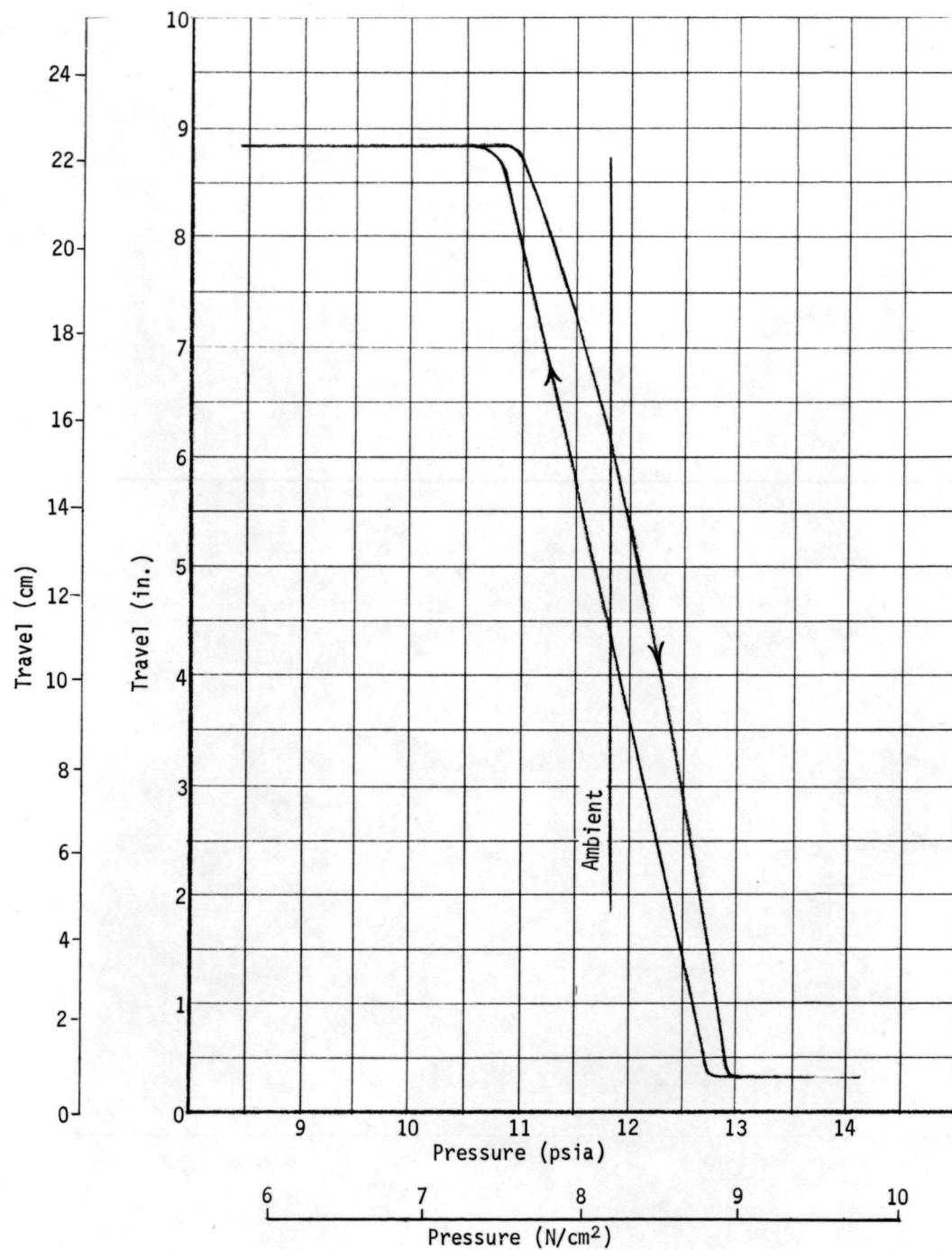


Figure 27 Bellows Deflection vs Pressure

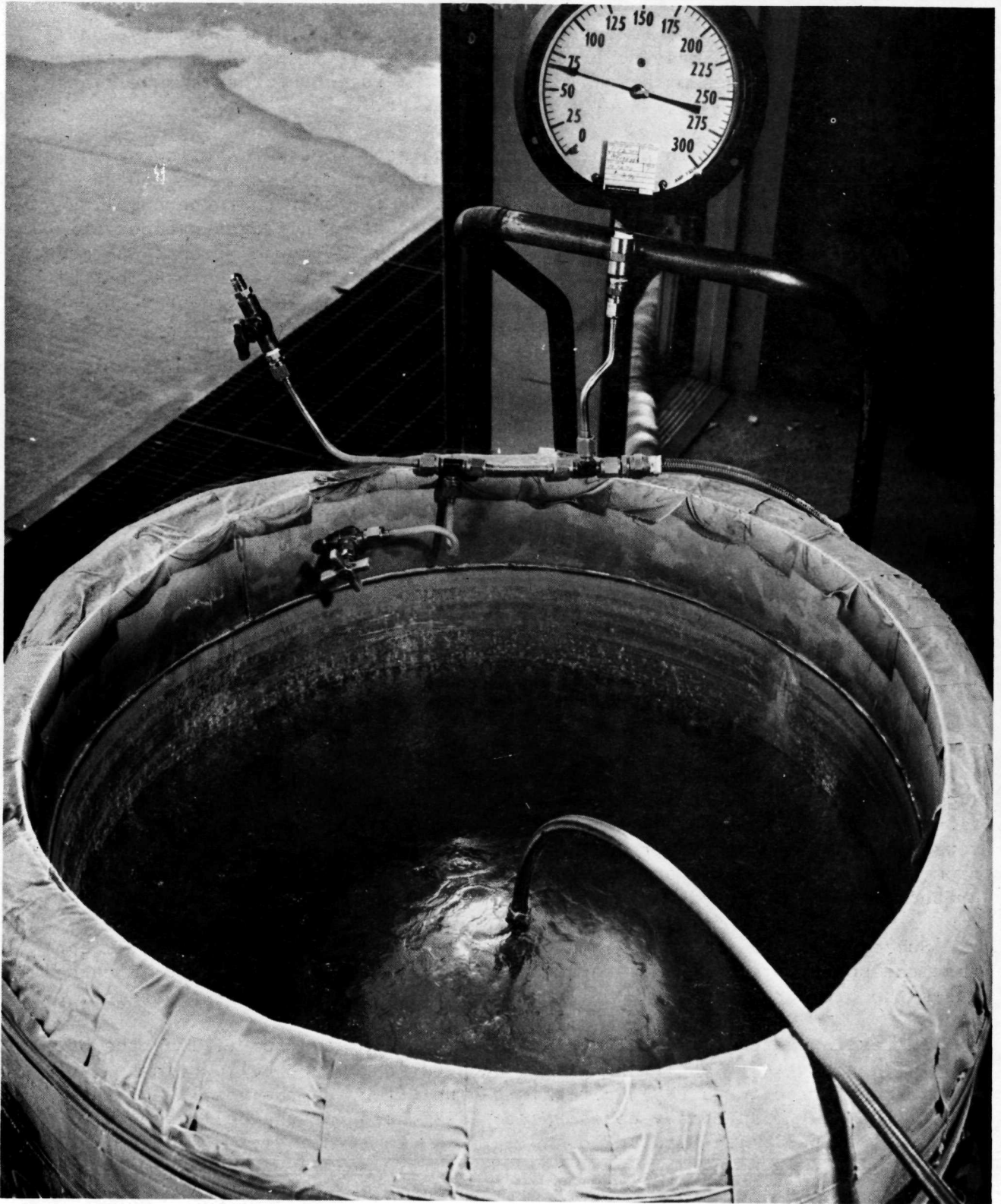


Figure 28 Bellows Assembly 8 Being Chilled during Pressure Test

- 6) The GN_2 source was reconnected to the gas side of the assembly, and an attempt was made to pressurize the assembly. Excessive bubbling of the nitrogen bath was observed in the region of the bellows flange, indicating the presence of a leaky gasket.

The test was then terminated, and the apparatus secured. Following warmup of the assembly, the bolt torque was checked and found to still be 160 in.-lb (18.1 N-m). It was concluded after reevaluating the test that the bubbling was probably the result of heat input from the gaseous nitrogen pressurant rather than leakage through the gasket. Therefore, a second attempt was made to conduct the pressure test following the same procedures as before, but with the bolts torqued to 200 in.-lb (13.8 N-m). No leakage was evident with the application of a slight positive pressure, so the test proceeded as follows:

- 1) The nitrogen pressure was gradually increased until it reached 265 psig (183 N/cm^2 , g), then maintained at this value for 5 minutes (300 sec). There was no evidence of leakage;
- 2) The pressure was vented slowly to ambient, then the liquid side of the bellows was pressurized slowly to 5 psig (3.45 N/cm^2 , g) with the helium, extending the bellows, and expelling LN_2 from the gas side of the bellows;
- 3) The helium pressure was increased to 12 psig (8.3 N/cm^2 , g) and held for 5 minutes (300 sec) to demonstrate the capability of the bellows to withstand an internal pressure of one atmosphere;
- 4) The test was secured by draining the LN_2 from the container, and venting the pressure from both sides of the bellows while the assembly warmed up.

Following the pressure test, the bellows assembly was leak-checked by evacuating the gas side of the bellows with the CEC leak detector while the liquid side of the bellows was pressurized with helium. There was no indication of leakage. Then the helium was vented, and the liquid side of the bellows assembly sealed. After complete warmup, the bellows assembly was removed from the pressure vessel and carefully inspected. No damage or other discrepancies were observed.

Subsequently, assemblies 6 and 8 were tested in a similar manner, except that the bolts were initially torqued to 200 in.-lb (13.8 N-m), and in both cases the pressure test was completed satisfactorily on the first attempt.

In testing assembly 8 a different technique was used for filling the bellows with nitrogen (the nitrogen was condensed inside the bellows instead of being transferred in as LN_2), but this had no effect on the results of the test. The only discrepancy noted was the distortion of the bellows neck as previously experienced with bellows 5.

E. LN₂ PROOF CYCLES, BELLOWS 5, 6, AND 8

The final step in the proof test of the three bellows assemblies was to subject them to five complete cycles at LN₂ temperature. Again the tests covered a relatively long time span, but the basic procedure did not change. Briefly, the steps employed in cycling the bellows were as follows:

- 1) The bellows assembly was installed in the exercise fixture;
- 2) A pressurization/vent line was connected to the liquid side of the bellows to provide an alternate source of helium pressure and vacuum;
- 3) The bellows assembly (installed in the exercise fixture) was placed in the insulated container, and the container filled with LN₂ to submerge the bellows assembly;
- 4) The assembly was evacuated with a vacuum pump to compress the bellows, then helium was introduced at a slight positive pressure to fully extend the bellows. This sequence was repeated for a total of five cycles;
- 5) The LN₂ bath was drained, and the assembly allowed to warm up;
- 6) The bellows assembly was removed from the bath, the pressurization/vent line disconnected (after closing the hand valve on the bellows outlet line), and the assembly transferred to the vacuum bench for a leak check;
- 7) The leak check was conducted with the CEC leak detector in much the same manner as for the pressure tests, except that this time the bellows was in the compressed condition with helium being applied to its exterior. No measurable leakage was detected in any of the three assemblies.

V. CYCLE TEST APPARATUS

The cryogenic cycle tests required the design and fabrication of a unique cycle test system that permitted remote cycling of the bellows, as well as related purge and leak check operations. Evolution of the design and selection of specific components for the system, were influenced primarily by two factors, i.e., the working fluid was fluorine, and *in situ* leakage measurements of the bellows were required. The use of fluorine in the system required that all components be fluorine-compatible (both chemically and cryogenically), that the system be scrupulously clean and maintained at a positive pressure at all times to preclude inflow of contaminants, that all incoming fluids be free of contaminants, and that essentially all test operations be controlled and monitored remotely.

The necessity for conducting an *in situ* leak check of the bellows at frequent intervals during the cycle tests considerably complicated purge and vent systems. Proper operation of the leak detector necessitates a vacuum-tight, fluorine-free system. Consequently, a leak-check concept was evolved where the bellows is leak checked in the extended condition (leak detector connected to the pressurization side of the bellows) after helium has been purged into the liquid side to displace the fluorine.

Detailed testing concepts and associated hardware configurations changed slightly during the course of the cycle test program as operational experience with the system was obtained. Some of these changes are discussed in the following paragraphs. The major features, however, remained essentially unchanged.

A. SYSTEM CONFIGURATION AND OPERATIONAL CONCEPT

To accomplish the cryogenic cycle tests, the system shown schematically in figure 29 was evolved. The major components of this system are as follows:

- 1) A fluorine supply tank that provides the fluorine for filling the bellows, and receives the fluorine expelled from the bellows;
- 2) The bellows assembly (complete positive expulsion device) that is undergoing test;
- 3) Interconnecting piping and associated valves that direct the flow of fluorine between the supply tank and bellows;
- 4) A vacuum-jacketed cryostat and a foam insulated tank that provide LN_2 baths to maintain the fluorine system at cryogenic temperature;
- 5) Pressurization, vent, and purge systems as required to control the flow through the system;
- 6) Instrumentation for monitoring system performance;

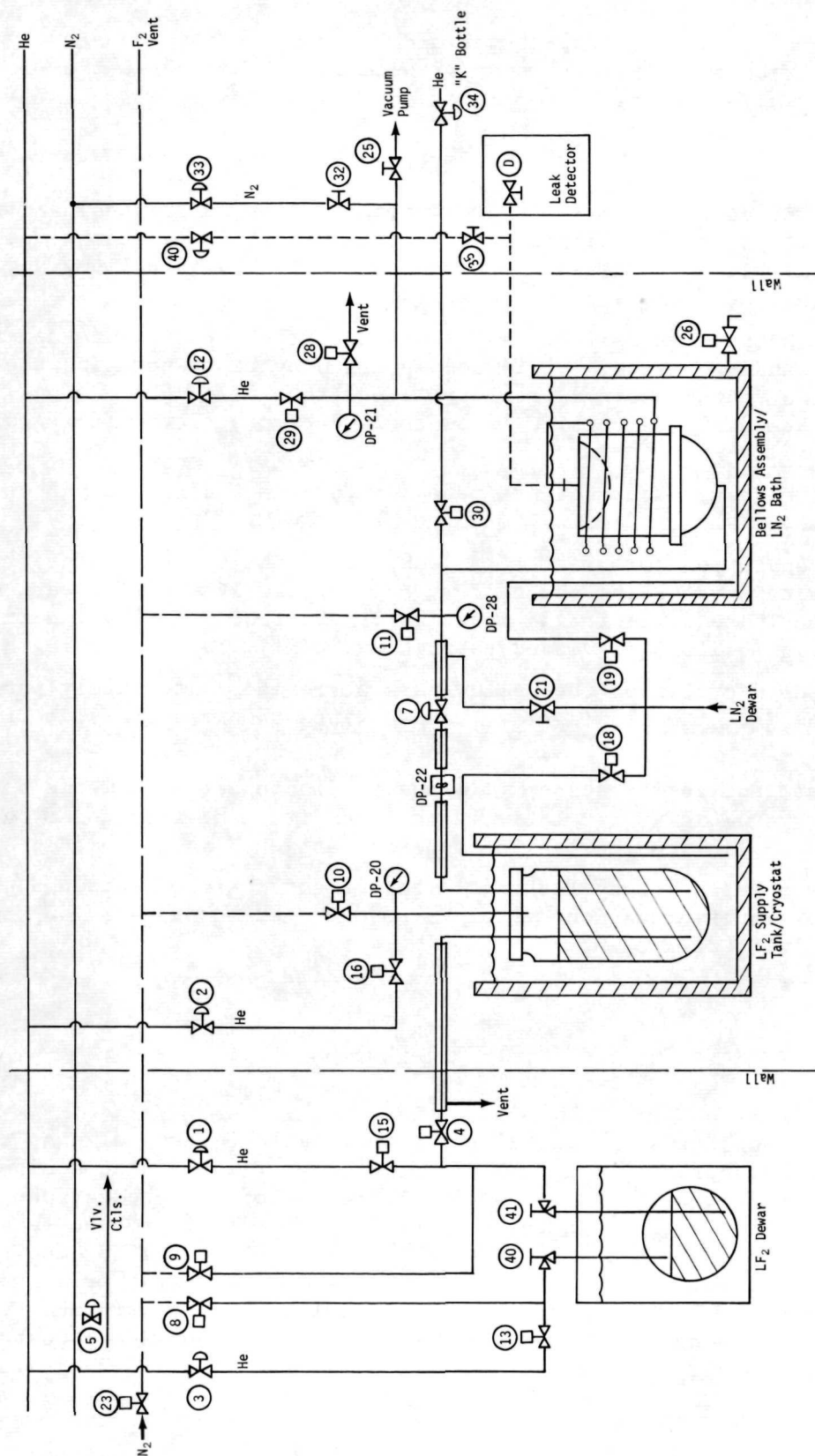


Figure 29 Schematic of Cycle Test Apparatus

- 7) A small fluorine storage dewar and interconnecting transfer system that is used to fill the system initially, and receive the fluorine after cycle testing is completed.

Briefly, the operational concept of the system is as follows:

- 1) With the bellows initially pressurized (fully compressed) and the supply tank filled with fluorine, the bellows is filled by opening control valve 7, pressurizing the supply tank with helium, and venting the bellows pressure through valve 28;
- 2) Once the bellows is full, as determined from the pressure and flow-rate readings, expulsion is accomplished by repressurizing the bellows to the desired pressure level, then venting the supply tank. Flowrate during expulsion is controlled by proper throttling of valve 7;
- 3) The foregoing sequences are repeated for the desired number of cycles;
- 4) In preparation for an *in situ* leak check, the LN_2 is drained from the bath surrounding the bellows so that the system will warm sufficiently to boil off the majority of the residual fluorine in the bellows (boiloff is vented through valve 11);
- 5) Two purge cycles of the bellows are performed, alternately purging helium into the liquid side, and GN_2 into the pressure side of the bellows;
- 6) The pressurization system is manually disconnected from the bellows (the system is in a relatively safe condition at this point) and a vacuum line to the leak detector is attached in its place;
- 7) After a satisfactory leak rate measurement has been obtained, the bellows pressurization system is reconnected in preparation for resumption of cycling.

B. FACILITY INSTALLATION

The cycle test apparatus was installed in the fluorine test cells at the Propulsion Research Laboratory (fig. 30). The major portion of the equipment was installed in the enclosed cell shown in the center of the photograph, the fluorine storage dewar is shown in the open cell on the left, and the leak detector and associated equipment was situated in the high bay cell on the right. This separation of equipment into three areas protected the dewar from the relatively hazardous cycle test operations, and also permitted personnel to accomplish the leak check without being directly exposed to hardware containing fluorine. The portion of the cycle test system installed in the center cell is shown in use during LN_2 cycle testing in figure 31.

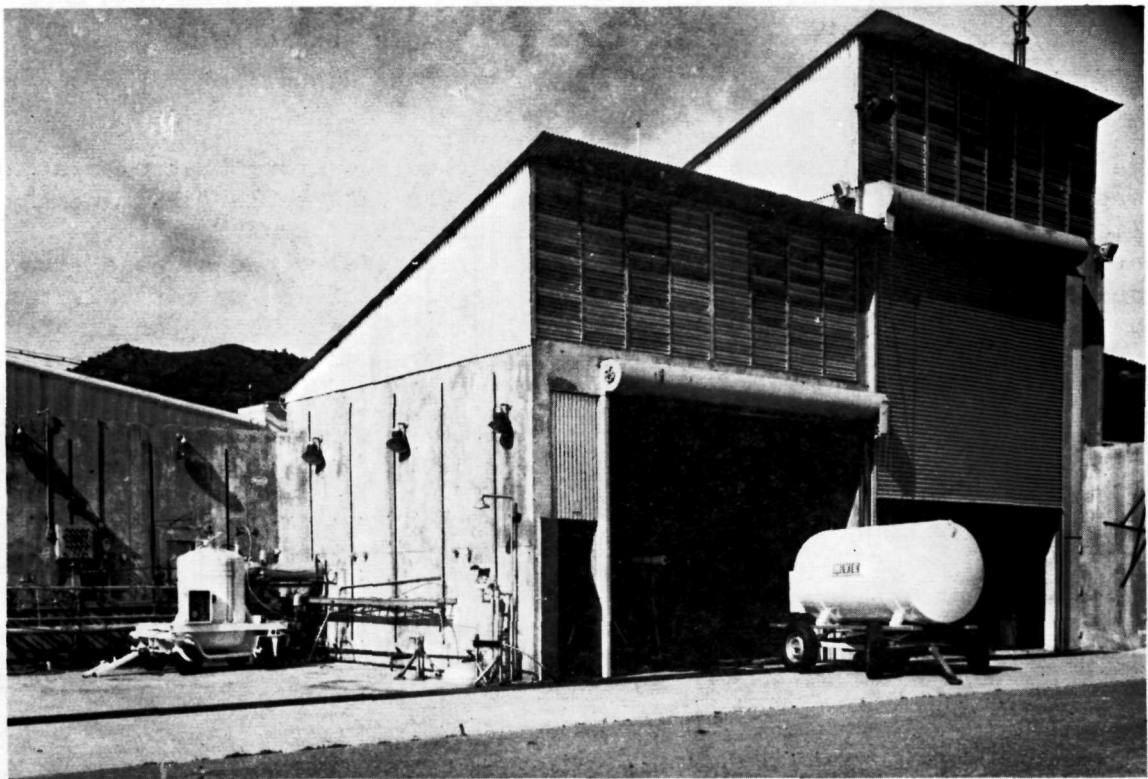


Figure 30 Fluorine Test Cells, Propulsion Research Laboratory

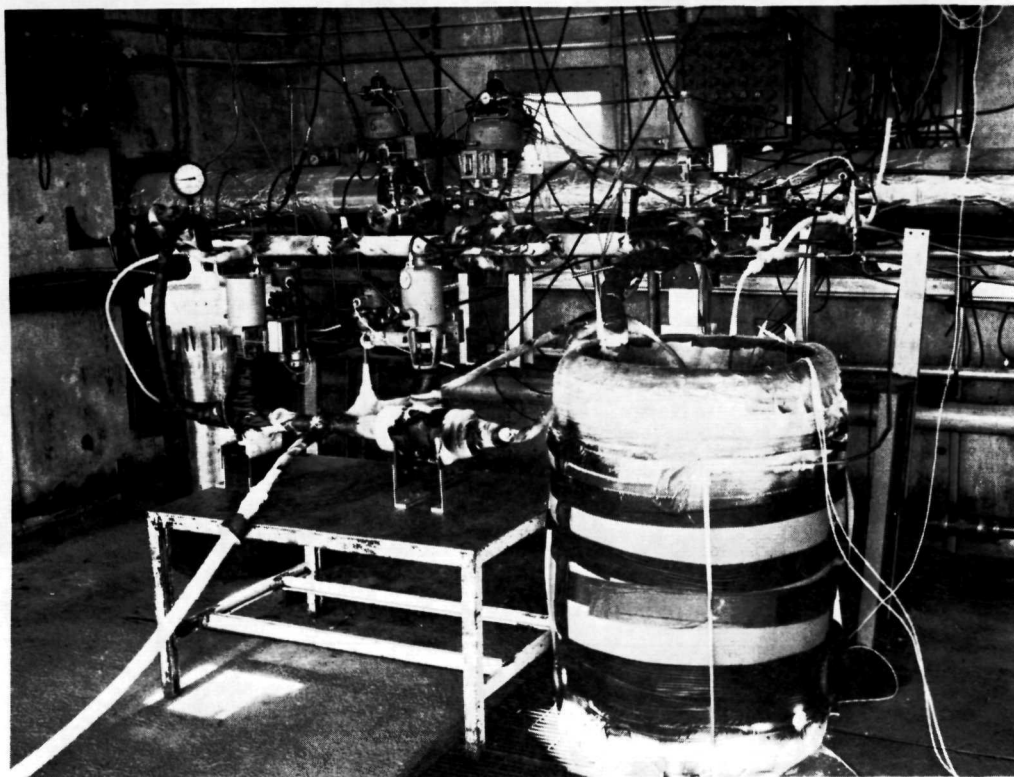


Figure 31 Cycle Test Apparatus during LN_2 Cycle Tests

The leak detector and associated equipment in the high bay cell is shown in figure 32. This separation of equipment is also shown schematically in figure 29.

The test was controlled and monitored from the laboratory Control and Instrumentation Center located some distance from the test cells. Permanently installed control and instrumentation cabling between J-boxes in the test cells and patch panels installed in the control center channeled the signals from one area to the other. The control panel designed specifically for this test program is shown on the left in figure 33. The six Bristol strip chart recorders that were used to record the test data are shown on the right in figure 34.

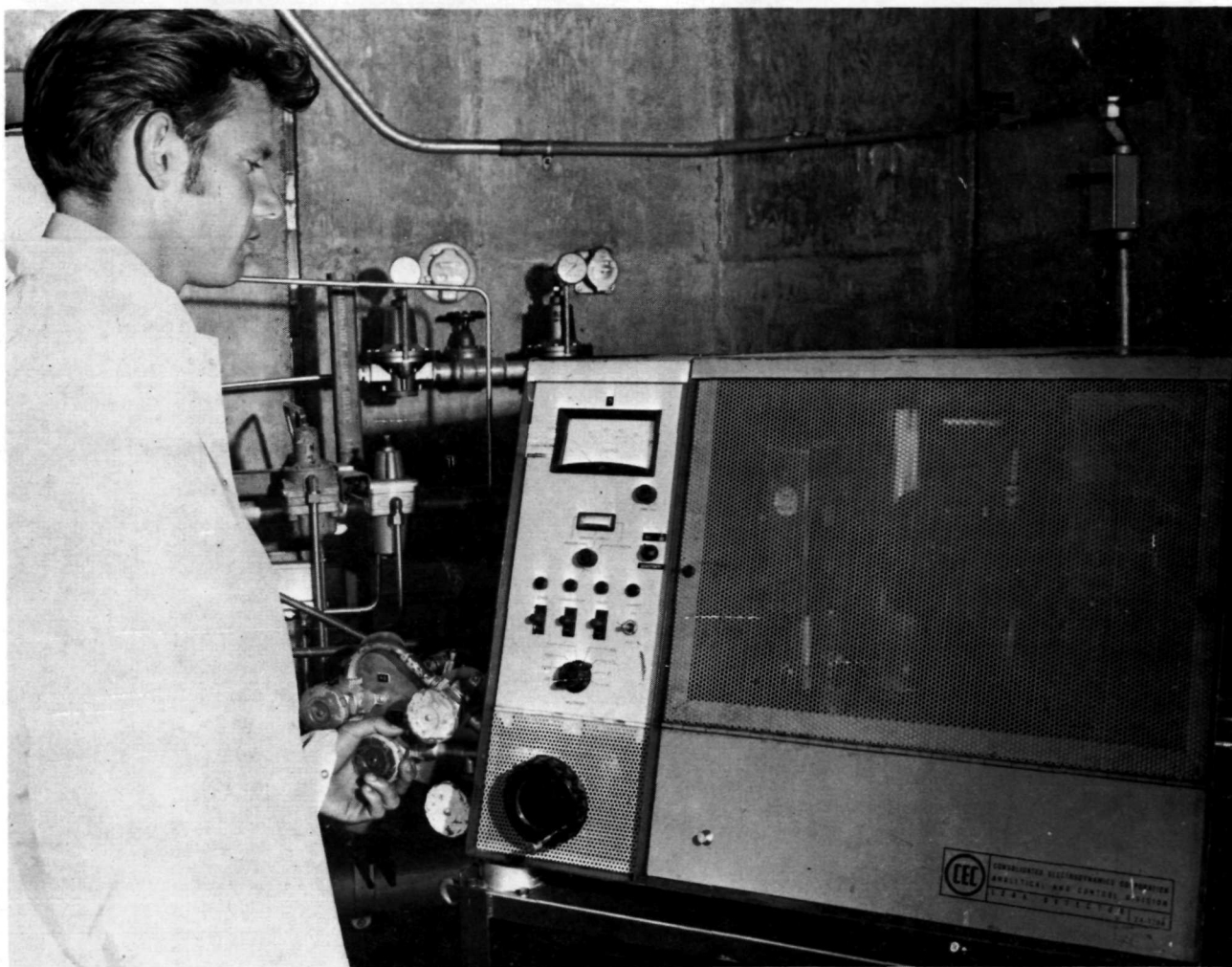


Figure 32 Leak Detector in High Bay Cell

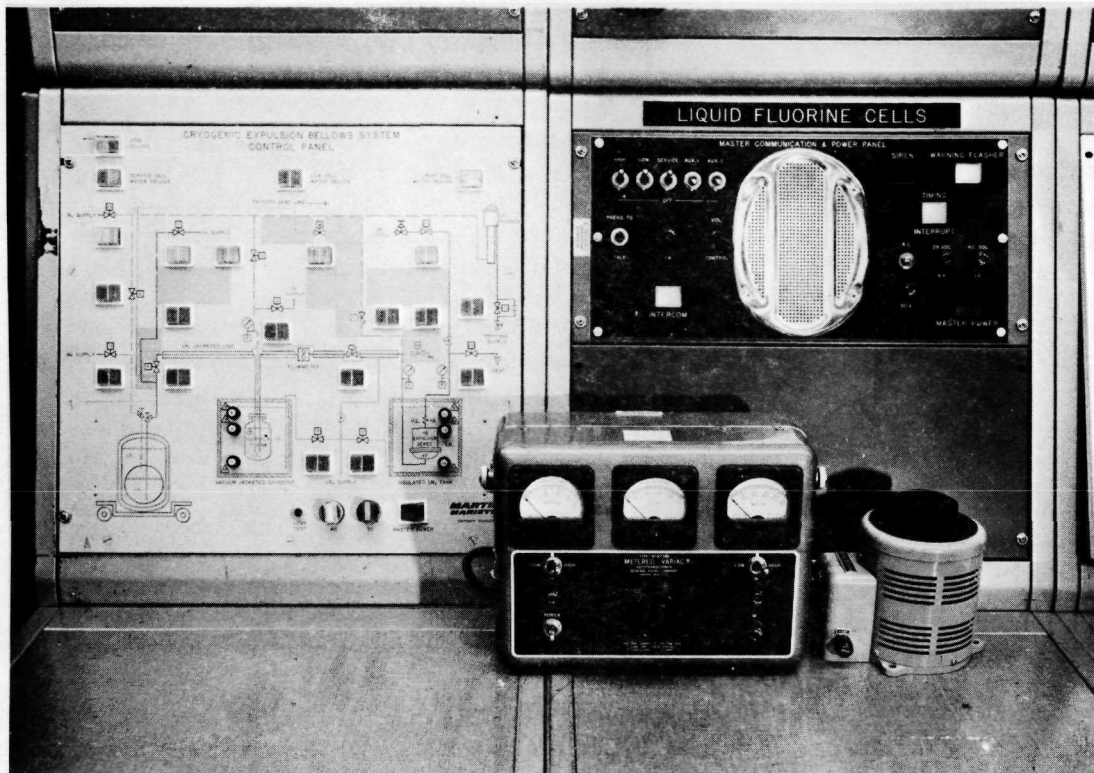


Figure 33 Control Consoles for Cycle Tests

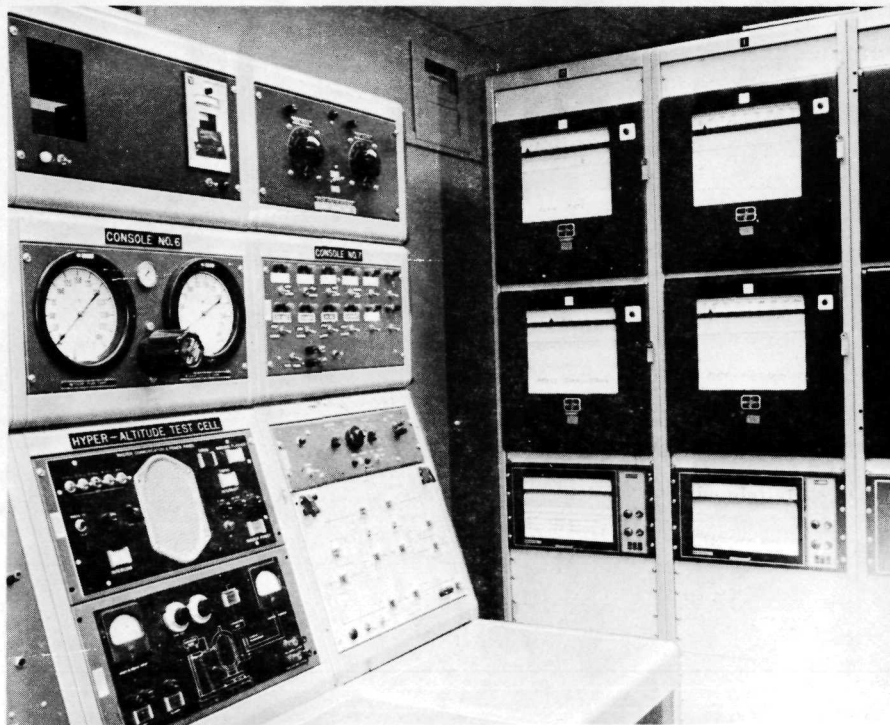


Figure 34 Strip Chart Recorders

C. SYSTEM COMPONENTS

The stainless steel fluorine supply tank used for the cycle tests (fig. 35) was designed and fabricated specifically for this program. It is constructed from two standard stainless steel 12 in. (0.305 m) pipe caps and a length of 12-in. (0.305 m) pipe, providing a capacity of 12 gallons (0.045 m³). A flanged connection at the top provides for the mounting of internal piping and instrumentation; a soft aluminum gasket seals the joint.

To maintain the fluorine supply in a subcooled condition, the supply tank is immersed in LN₂ in a 17-in. (0.43 m) diameter, 40-in. (1.02 m) deep vacuum-jacketed cryostat fitted with a thick foam cover. Heat leak into the cryostat is sufficiently low so that fluorine can be left in the supply tank overnight with no danger whatsoever of excessive boiloff. Nitrogen to fill the bath is provided from a 600-gallon (2.26 m³) mobile dewar through a remotely controlled valve (18).

An LN₂ bath for the bellows assembly is provided by a 15-in. (0.38 m) diameter by 25-in. (0.62 m) deep aluminum tank wrapped with 2-in. (5 cm) of polyurethane foam insulation. No cover is provided for the tank since a low heat leak is not essential. The bath is filled from the mobile dewar through valve 19. Remote draining of the bath is provided by valve 26. Two electrical heaters, one installed in the bottom of the tank and one in the upper inverted dome of the bellows assembly, are provided to accelerate the warmup of the assembly. These are controlled by Variacs located in the control center.

The interconnecting plumbing between the supply tank and bellows assembly is not completely submerged in LN₂, but the majority of the line (three sections) is jacketed with LN₂ to maintain the line and associated valves and instrumentation connections at cryogenic temperature. The sections of jacketed line are fabricated from standard sizes of stainless steel tubing, with bellows sections provided in the jacket to allow for differential expansion. The desired flow of LN₂ through the jacket is provided by proper throttling of valve 21.

The fluorine storage dewar used as a source of fluorine for the cycle tests is a triple-walled vessel designed and fabricated by Martin Marietta (shown on the left in fig. 30). The inner spherical vessel has a capacity of 35-gallons (0.13 m³) of LF₂, the intermediate jacket holds 85 gallons (0.32 m³) of LN₂ to maintain the LF₂ subcooled, and the outer vacuum jacket contains multilayer insulation to minimize the heat leak. The dewar is fitted with hand valves on the pressurization/vent line and the inflow/outflow line. A portion of the transfer system between the dewar and fluorine supply tank is also LN₂-jacketed to minimize fluorine vaporization. This jacket is in series with the other three sections of LN₂-jacketed tubing.

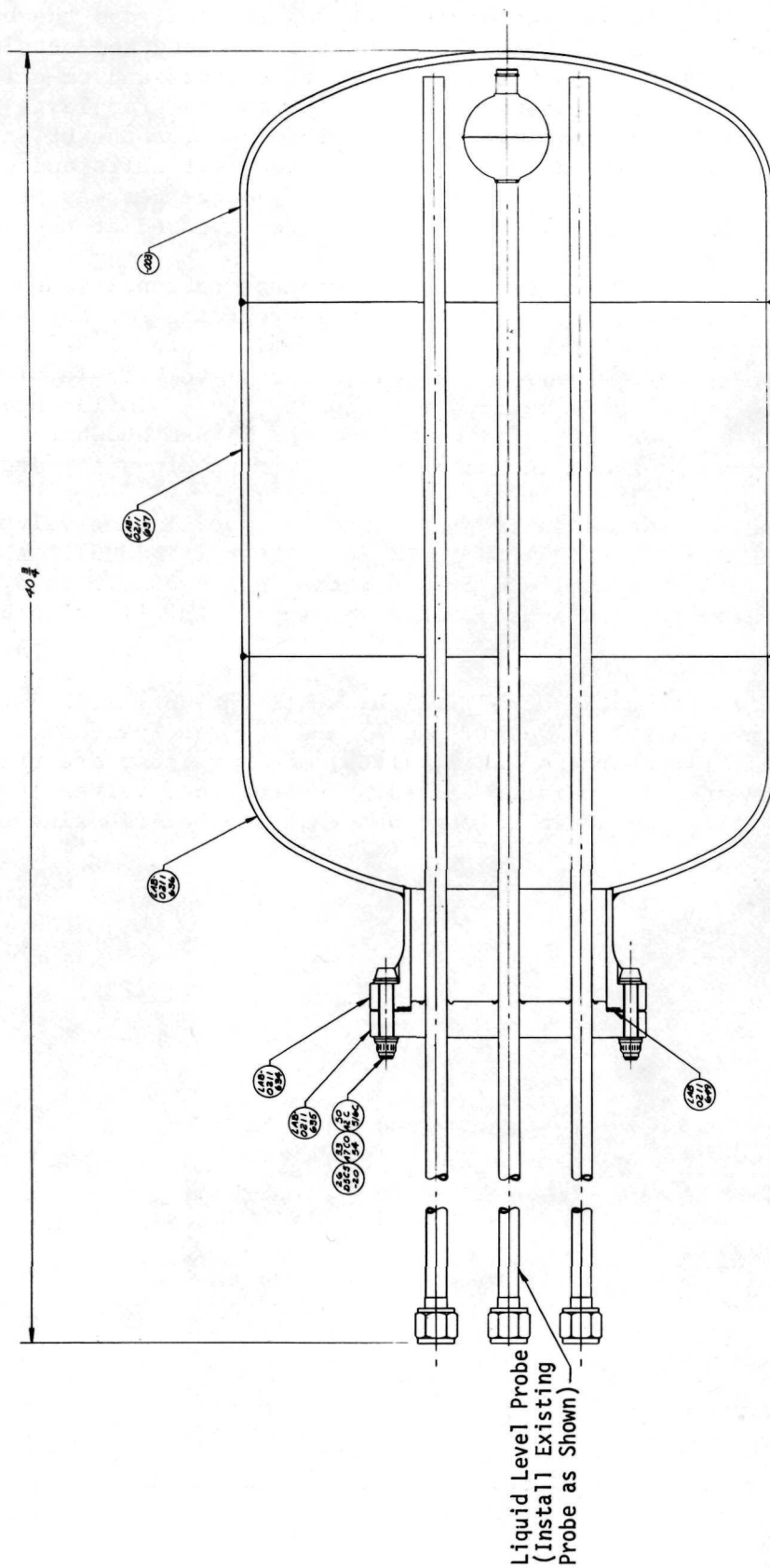


Figure 35 Fluorine Supply Tank

Helium pressurization of the storage dewar, the supply tank, and the bellows assembly is provided from a helium manifold that runs along the outside wall of the test cells, through appropriate pressure regulators and on-off valves. Helium for the LN_2 cycle tests was obtained primarily from large storage bottles located at the nearby Cold Flow Laboratory. For the LF_2 cycle tests, a helium bottle trailer was parked adjacent to the test cells and connected directly into the helium manifold (Fig. 36). GN_2 purge gas was provided from a separate manifold that connects to storage bottles located at the CFL.

The helium used to pressurize the bellows was temperature conditioned by means of a heat exchanger installed in the LN_2 bath surrounding the bellows assembly. The heat exchanger consists of a 20 ft (6.1 m) length of 3/8-in. (9.5 mm) diameter copper tubing, wrapped in a coil approximately 15-in. (0.38 m) diameter by 8-in. (0.2 m) high. Previous experience with a similar heat exchanger used to test a bellows in liquid hydrogen (ref 3) had shown that the helium outlet temperature approached the bath temperature within a few degrees.

Venting of the fluorine system was provided through several vent valves into a manifold and vent stack fitted with a propane burner (fig. 36). A continuous purge of GN_2 into the manifold prevents the inflow of air into the system; the propane burner provides a means of disposing of the fluorine boil-off in a safe manner.

The valves exposed to either LF_2 or GF_2 in the system are primarily of two types. The fluorine flow control valves (4 and 7) and the vent valves (8, 9, 10, and 11) are pneumatically operated Annin valves; the remainder are primarily Hoke solenoid or manually operated valves. In addition, valves 18 and 19 that control the LN_2 flow are Annin valves, but they are not fluorine compatible.

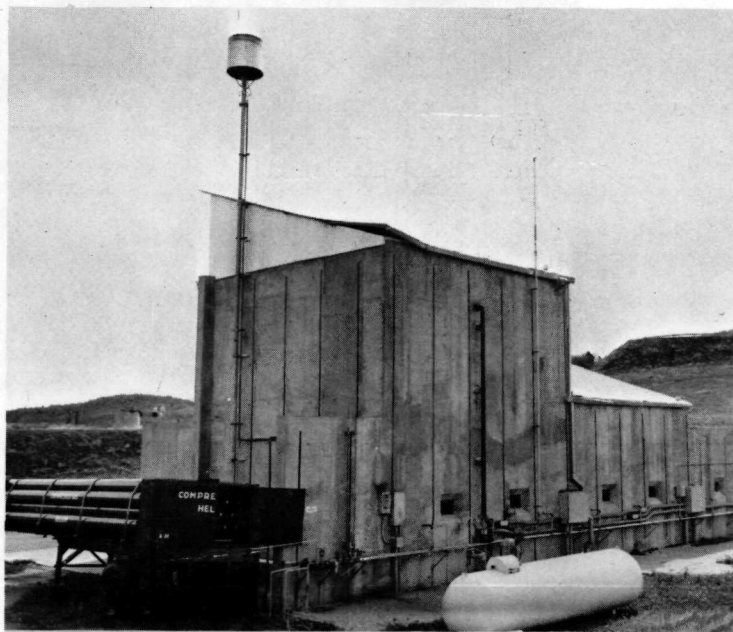


Figure 36 Rear of Cells Showing Helium Trailer and Vent Stack

D. INSTRUMENTATION

Instrumentation was provided to measure pressure, temperature, flowrate, and liquid level as required to satisfactorily accomplish the test. Extreme accuracy of data was not essential in satisfying the major test objectives, but good accuracy was essential to monitor test operations. The need to continuously maintain a slight positive pressure in the system, yet not subject the bellows to an internal differential pressure greater than 15 psi (10.3 N/cm²), imposes rather stringent accuracy requirements on the pressure measurements.

Three pressure measurements were provided: the supply tank pressure, the pressure on the liquid side of the bellows, and the bellows gas-side pressure. Taber strain gage transducers, used with Bridge Power Supply and Balance Units, provide the signals recorded on the Bristol strip chart recorders. Measurement accuracy is assured by initial end-to-end calibrations using a deadweight tester, augmented by a shunt calibration of each measurement at the beginning of each day's test operations.

Fluorine flowrate during cycle testing is measured with a Potter turbine meter whose output is conditioned by a Pottermeter Frequency Converter, and recorded on a Bristol strip chart. Measurement accuracy is assured by daily calibration of the recording system with a signal generator, using flowmeter calibration data provided by the manufacturer.

Liquid level in the fluorine supply tank is measured by a magnetic float switch assembly that senses discrete levels at $\sim 1\frac{1}{4}$ -in. (3.2 cm) intervals from the bottom of the tank to the top. Output is again recorded on a Bristol strip chart recorder.

Level of the LN₂ in the two baths is monitored by probes employing carbon resistors as the discrete sensing elements. Output is displayed by indicator lights contained in the Cryogenic Research Company, Model LP-10 Liquid Level Indicator. The output light is red when the resistor is exposed to a gaseous environment, blue when immersed in liquid.

Three thermocouples were provided to measure the approximate temperature of the bellows assembly during periods of cooldown and warmup. One of these is installed on the heat exchanger, one is tack-welded to the upper inverted dome of the bellows assembly, and the other to the lower dome. All three temperatures are recorded on a single Bristol recorder through a conditioning system that includes an ice point reference bath and a low-speed scanner that selected one thermocouple at a time for output recording. System accuracy is assured by periodic calibration, inputting voltages corresponding to known thermocouple outputs obtained from National Bureau of Standards tables.

E. FINAL ASSEMBLY AND CHECKOUT

The cycle installation was nearly completed in December 1969, but numerous final plumbing and electrical interconnections were not completed until many months later when an acceptable bellows assembly first became available for installation in the system. These remaining uncompleted tasks were accomplished in August 1970 upon completion and proof testing of bellows assembly 5. These tasks included the following:

- 1) The electrical/instrumentation system was completed, including -
 - a) Installation, checkout, and calibration of the three pressure transducers, the turbine flowmeter, the fluorine supply tank liquid level sensor, the LN_2 bath level sensors, and three thermocouples on the bellows assembly and helium heat exchanger,
 - b) Installation and checkout of the pneumatic controller for the fluorine throttling valve,
 - c) Operational check of all valves in the system;
- 2) Recleaning the fluorine supply tank following the detection of a small amount of contamination in it;
- 3) Interconnecting piping was installed, including -
 - a) The tubing connecting the LN_2 jacketed transfer line to the dewar, to the LF_2 supply tank, and to the bellows assembly,
 - b) The helium pressurization line connecting the facility supply to the LF_2 supply tank,
 - c) The helium pressurization line connecting the facility supply through the coiled heat exchanger to the bellows assembly.

In addition, several modifications were incorporated to update the system in accordance with the latest operational concepts. These included:

- a) Relocation of the GN_2 purge system to provide a nitrogen purge to the fluorine side of the bellows through a separate on-off valve,
 - b) Replumbing of purge lines from common pressure manifolds to individual regulators,
 - c) Provision of helium for leak-check purposes from a K-bottle rather than from the facility supply system;
- 4) The helium tube trailer was parked in position at one end of the test cells and connected into the facility manifold. Subsequently, the system was checked for contamination. The particle count was found to be satisfactory, but the hydrocarbon content was too high (30 ppm). Following a system purge with nitrogen, the hydrocarbon content was acceptable (~ 10 ppm);

- 5) Two checkouts were performed with LN_2 to identify problems relative to system purging, pressurization, and propellant transfer. The first attempt to transfer LN_2 was unsuccessful because of excessive leakage through the fluorine throttling valve. The valve was re-adjusted, and the second checkout test was successful. Checkout included the following:
- a) Electrical check of each valve,
 - b) Operational test of all valves, including the pneumatic controls and the regulator settings,
 - c) Transfer of LN_2 into the fluorine supply tank and through the fluorine flow system, but without cycling of the bellows.

Upon completion of the foregoing, the system was considered ready for the initial LN_2 cycle tests.

VI. LN₂ CYCLE TESTS, BELLWS ASSEMBLY 5

The primary objective of the LN₂ cycle tests was to verify the design of the entire expulsion device (particularly, the bellows), before an assembly is tested in liquid fluorine. In particular, it was desired to verify that the cycle life was in excess of 100 cycles so that there would be no danger of catastrophic failure in fluorine. Additionally, the LN₂ cycle tests demonstrated the operational capability of the entire cycle test installation (particularly, the unproved leak check concept), developed the step-by-step test procedures that would be used with fluorine, and also provided preliminary statistical data regarding the effect of fluorine versus nitrogen on cycle life.

Because cycle life was assumed to be in excess of several hundred cycles, relatively large numbers of cycles were planned between leak checks. The cycle tests themselves are not time consuming, possibly 3 to 5 minutes (180 to 300 sec) per cycle, but test operations associated with each leak check were estimated to require approximately a full working day. Therefore, it was important to hold the number of leak checks to a reasonable minimum.

The initial plan for the LN₂ cycle tests was to conduct a maximum of 500 cycles, with the leak checks performed after cycles 25, 50, 100, 200, 300, and 500. In general, this plan was followed in conducting the program, but with same minor deviations. The first series of 25 cycles was actually broken into three subgroups of cycles to permit the leak check procedure to be perfected without subjecting the bellows to a large number of cycles. At this point in the program it appeared that only two assemblies might be available for cycle testing, in which case it might be desirable to conduct some fluorine tests with assembly 5 in addition to the LN₂ tests. As it finally turned out, however, a third assembly finally was made available so that assembly 5 could be committed entirely to LN₂ cycling.

The test program also deviated somewhat from the plan in that the actual number of cycles conducted in each series was somewhat less than the planned number. This was done to account for the many cycles (and some half-cycles) that the bellows is subjected to during fabrication sequences (assembly, leak checking, cleaning, and X-raying), as well as the purge cycles associated with cycle testing. Adding these cycles to the number of fill/expulsion cycles actually conducted in each series of tests results in a total for each series that is equivalent to the planned total.

A detailed discussion of the entire LN₂ cycle test program is presented in the following paragraphs.

A. LN₂ CYCLES 1 THRU 6

The primary objective of this first short series of cycle tests was to provide an operational checkout of the entire cycle test apparatus, become familiar with the operational characteristics of the system, and evolve suitable test procedures. Since fluorine was not involved in these tests, it was possible to incorporate a number of shortcuts that greatly simplified test operations. These shortcuts include:

- 1) Operational personnel were allowed to work in the test cell throughout the entire cycle test sequence, and were not required to wear protective clothing;
- 2) A formal written procedure was not employed. Instead, the test sequences were improvised as required to evolve optimum procedures;
- 3) Basic ground rules requiring positive pressure in the fluorine system at all times and pressure backup of all fluorine pressurization valves were not always adhered to. A ground rule limiting the ΔP across the bellows in the extended position to 15 psi (10.3 N/cm^2) was strictly adhered to, however.

A total of six cycles was completed. Test conditions that remained fixed throughout the six cycles were:

- 1) The helium pressure regulator (valve 2) for fluorine supply pressurization was set at 10 psig (6.9 N/cm^2 , g);
- 2) The helium pressure regulator (valve 12) that pressurizes the bellows for outflow was set at 35 psig (24.1 N/cm^2 , g).

Conditions that were varied during the six cycles were the opening and closing sequence of the supply tank pressurization valve 16 and vent valve 10, bellows pressurization valve 29, vent valve 28, throttling valve 7, and the throttling position of valve 7. The primary purpose in experimenting with different valve sequences was to evolve a procedure that minimizes two-phase flow through the system and still achieves in a simple repeatable cycle with a minimum elapsed time.

Of the six cycles, the final one proved to be best. Pertinent data from the last cycle are shown in fig. 37. This cycle is characterized by the following principal features:

- 1) Throttling valve 7 remained open throughout the cycle. Bellows filling was initiated automatically by venting the bellows pressure through valve 28, and stopped once the bellows assembly was completely filled with liquid. Expulsion of liquid from the bellows was initiated by repressurization of the bellows through valve 29, and stopped automatically after the bellows reached its full travel;

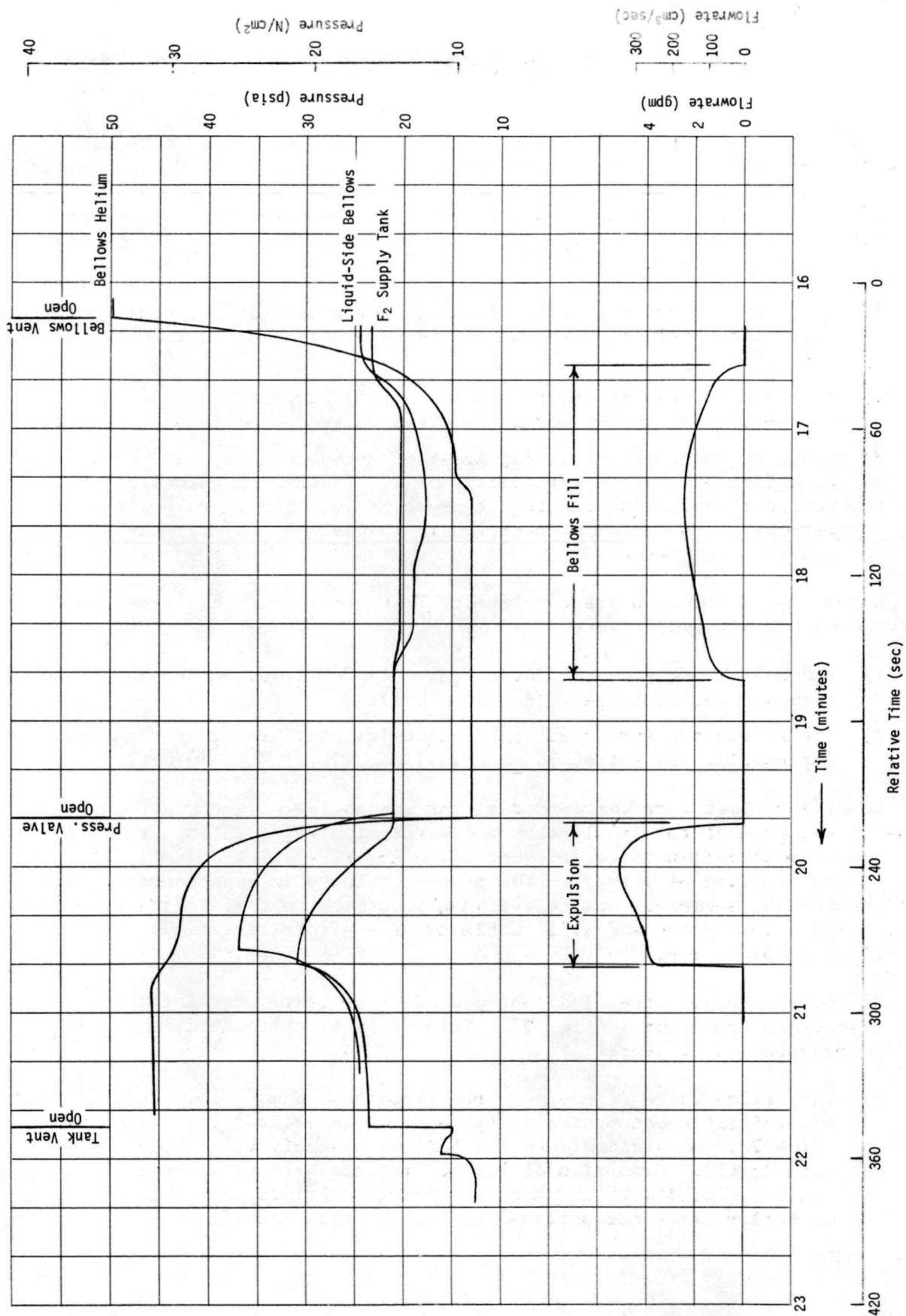


Figure 37 Typical LN₂ Cycle Test Data (9/1/70)

- 2) The supply tank vent valve 10 remained closed throughout the cycle, locking a positive pressure in the system that provided subcooling of the LN_2 and minimized vapor formation (and two-phase flow). During bellows outflow (refill of the fluorine supply tank) the supply tank pressure increased approximately 10 psi (6.1 N/cm^2), but returned essentially to the initial condition after the flow stopped and some of the nitrogen was recondensed;
- 3) The integrated flow through the flowmeter during bellows fill compares favorably with that during bellows outflow, and is approximately equal to the known bellows displacement, i.e., 4.6 gallons (0.017 m^3). The flowmeter recorded data exhibited some oscillations and a few spikes (not reproduced in fig. 37) indicative of the presence of some vapor in the system, but this was not serious. There appears to be no danger of damaging the flowmeter as a result of overspin.

The leak check procedure of the bellows following the sixth cycle was one of the simplest that could be envisioned, but not necessarily one that is feasible for LF_2 testing. The optimum procedure would probably involve two complete purge cycles of the bellows with GN_2 to eliminate the F_2 from the liquid side of the bellows, and the He from the pressurization side. In this case, however, no purge was employed. Purging of the liquid side (LN_2 with GN_2) would accomplish nothing; purging of the gas side was not accomplished simply to provide a worst-case situation with regard to pumpdown time. Obviously, a relatively long time is required to pump down the helium in the bellows to a low enough background level to permit a quantitative leak rate measurement to be made. This is the simplest technique and one that needed to be tried.

The first step in the leak check procedure was to drain the LN_2 from the bath surrounding the bellows assembly. This permits the bellows to warm up sufficiently to vaporize the excess liquid from the assembly. Actually, this step was not accomplished until the day after completion of the cycle tests.

Next, the connection was broken between the helium heat exchanger and the bellows pressurization inlet line, and the latter was connected to the CEC leak detector. Connection of the leak detector at this point in the system minimizes potential pumpdown problems arising from leakage through valve seats and system joints.

The leak detector was placed in operation and pumping was continued all day and throughout the night before the helium background level was reduced to an acceptable value. Presumably, the pumpdown time could be reduced considerably by using a higher capacity pump than that contained in the leak detector, but this was not considered for this initial test. The bellows assembly was found to be leak tight; i.e., leakage $< 10^{-7} \text{ scc He/sec}$.

B. SYSTEM MODIFICATIONS

Following the first short series of LN_2 cycle tests, a number of modifications were made to the cycle test apparatus. The majority of these were necessitated by safety considerations; i.e., the eventual use of LF_2 in the system wherein test operations must be conducted remotely. In addition, several other modifications were incorporated based on experience gained in the LN_2 cycle tests. The most significant of the modifications are described below.

- 1) The helium heat exchanger, a coil of 3/8 in. (9.5 mm) copper tubing, was lowered to surround the expulsion device instead of being mounted above it. This permits a smaller amount of LN_2 to be used in the bath, and also reduces the draining time following the cycle tests;
- 2) The hand valve used to drain the LN_2 from the bath (valve 26) was replaced by a pneumatically operated remote valve so that draining can be accomplished without the need for personnel to enter the test cell;
- 3) Valves 18 and 19 that control the LN_2 to the baths surrounding the LF_2 supply tank and the expulsion device were insulated with foam to reduce the heat leak into the system;
- 4) Hand valve 21 that controls the flow to the LN_2 jackets was replaced by a valve with a longer stem to eliminate a freezing problem encountered in the initial tests;
- 5) Valve 16 was relocated closer to the inlet to the LF_2 supply tank to minimize the length of plumbing exposed to the fluorine;
- 6) Short stainless steel spool pieces were installed in place of the original copper ones at the junctions of valves 11, 17, and 30 to minimize heat transfer from the valves into the system;
- 7) The insulation was removed from all plumbing connections in the fluorine system to minimize the fire danger in the event of fluorine leaks. This included valves 7, 11, 17, and 30, and two pressure transducers;
- 8) The orientation of valves 17 and 30 was rechecked to assure that only the underside of the seat would be exposed to fluorine, not the bellows packing gland;
- 9) The helium supply line to the liquid side of the bellows (valve 17) was extended into the high bay cell so that helium purging could be conducted remotely;
- 10) A nitrogen purge/evacuation system for the bellows was installed as shown in fig. 29 (valves 33, 32, and 25) to permit dilution of the helium in the bellows prior to leak checking;
- 11) A combination of copper tubing and vacuum hose was installed (shown dotted in fig. 29) to permit operation of the leak detector from the adjoining high bay cell instead of the fluorine cell;
- 12) Control wiring was relocated to keep it as far from the fluorine flow system as possible and thereby minimize fire danger.

Upon completion of the foregoing modifications the entire cycle test system was leak checked. External leaks were detected by means of a bubble check after pressurizing the system to 40 psig (27.6 N/cm², g). Valve seat leakage was detected by system pressure decay during a long time interval. Only a few minor leaks were found at some of the AN tube connections and these were readily corrected by retorquing the tube nuts.

C. LN₂ CYCLES 7 THRU 11

This second short series of cycle tests was conducted to check out the modified test apparatus and the preliminary test procedure that was evolved from the initial series of tests. Helium for these tests was supplied from the large storage bottles located at the Cold Flow Laboratory rather than the helium tube trailer previously used.

The valve operating sequence employed for these five cycles was essentially the same as that employed in the earlier tests, but the results were somewhat poor. There was considerable evidence of excessive vapor in the system, probably the result of inadequate insulation of the transfer lines and valves. Ultimately, however, a heavy layer of frost built up on the system, and the final cycles were relatively good. Pertinent pressure and flowrate data for the last cycle is presented in fig. 38 together with the valve opening and closing sequences. The majority of the flow resulting from the venting of the LF₂ supply tank (valve 10 open) is probably vapor rather than liquid.

D. LN₂ CYCLES 12 thru 15

An additional short series of cycles was conducted preparatory to conducting a complete purge and leak check of the bellows assembly. The cycles were conducted using the same procedures as before, but with two changes in configuration. First, the valves and plumbing connections were reinsulated to reduce the heat leak into the system and the resultant formation of vapor. Secondly, some of the LN₂ was purged from the fluorine supply tank to reduce the tank pressure rise during bellows outflow. The supply tank was approximately 90% full during the previous series of tests; it was only 75% full for this series of tests.

Only four cycles were conducted, and the results were not significantly different from those previously obtained. The presence of some vapor in the system was still evident, but acceptable results were obtained without waiting for a build up of frost on the system.

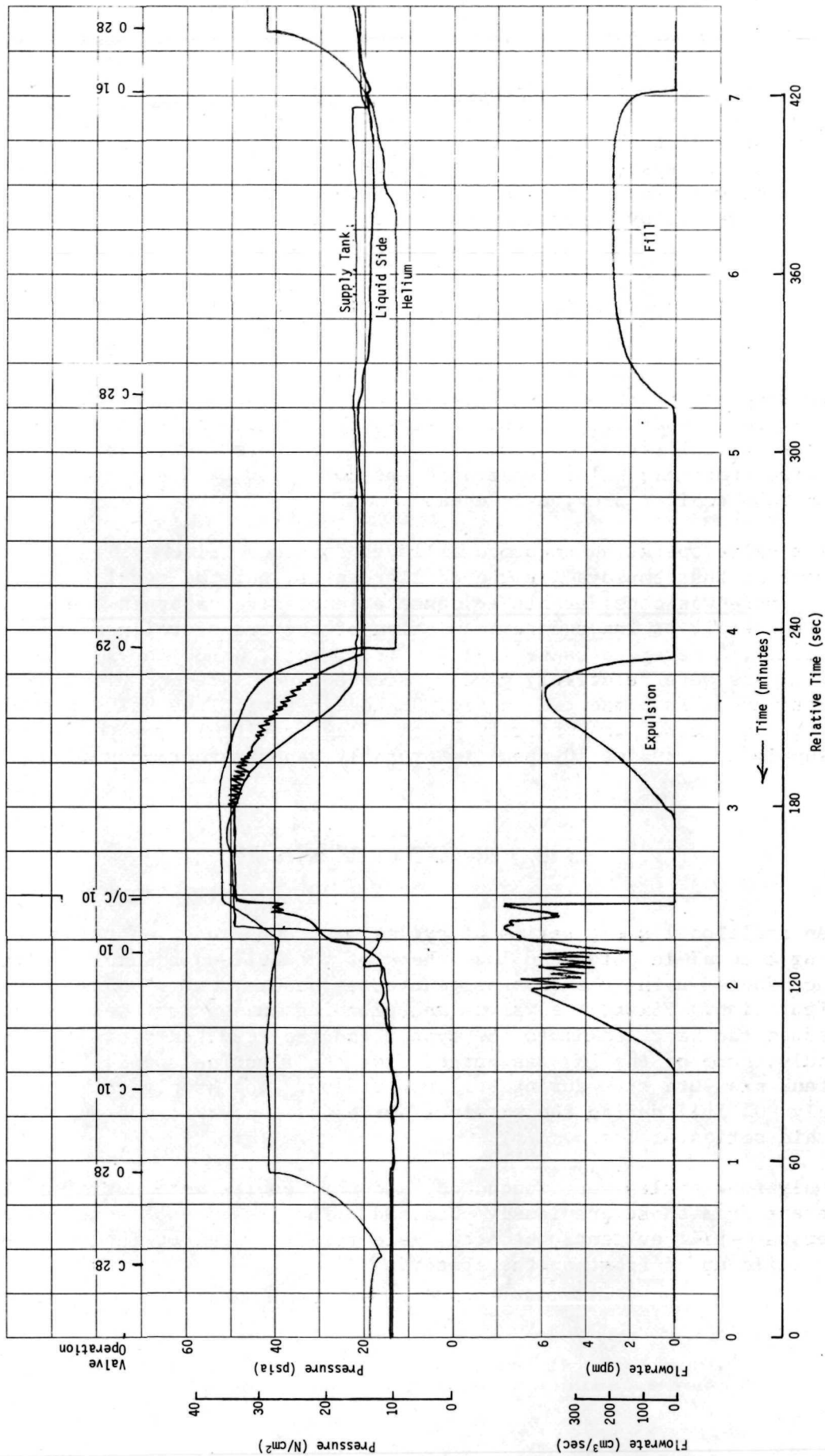


Figure 38 LN₂ Cycle Test Data, Cycle 11

Upon completion of the cycles, the purge sequence was begun preparatory to leak checking. Originally it had been planned to purge the GF_2 from the system with GN_2 , then introduce helium into the system only after the leak detector had pumped the bellows down and was ready for a measurement. The technique actually adopted, however, was to skip the GN_2 purge, and purge helium directly into the system. This technique has a significant advantage regarding simplicity, but it does introduce a complication into the leak check in that the helium is already present when the system is being evacuated for leak checking. In the event of a leak through the bellows, there will be a continual flow of helium into the detector during pumpdown, but eventually a steady-state reading will be obtained, and this will be the true leak rate of the bellows.

The first step in the purge sequence was to drain the LN_2 bath and allow the bellows assembly to warm up. The drain operation required approximately 45 minutes (2700 sec) because of the small size of the valve and associated fittings. At the end of this time draining still was not complete, however, because the valve is actually located approximately 2 in. (5 cm) above the bottom of the vessel. The need for a modification to the drain connection was evident.

The system was allowed to warm up for approximately 1 hr, but this proved to be a very slow process because LN_2 remained in the bottom of the vessel. Then for a period of approximately 30 minutes (1800 sec) attempts were made to vent the remaining nitrogen from the liquid side of the bellows by cycling the vent valve (valve 11), but with little overall effect. The pressure dropped abruptly to atmospheric each time the vent valve was opened, but as soon as the valve was closed, the pressure spiked and then returned to essentially its previous value (approximately the vapor pressure corresponding to the temperature of the nitrogen remaining in the bellows). The pressure spike is not clearly understood, but apparently results from a slight delay in the suppression of LN_2 boiling after system pressure has reached the saturation value. The pressure traces obtained during this time period are produced in fig. 39.

After allowing another 45 minutes (2700 sec) for further warmup, the liquid side of the bellows was again vented by cycling valve 11. This time the results were considerably better. The pressure was reduced from 47 to 35 psia (32.4 to 24 N/cm^2) during a 9-minute (540 sec) interval in which the valve was operated 11 times. These pressure transients are also shown in fig. 39.



An additional 30-minute (1800 sec) warmup period ensued, then an electric heater was used to hasten the evaporation of the LN_2 remaining in the bottom of the vessel. By the time all the liquid had been evaporated, 3 hr had elapsed since the opening of the LN_2 drain valve. Just before initiation of the purge sequence, a final venting of the system was accomplished. Two cycles of the vent valve reduced the system pressure from 18 to 13 psia (12.5 to 9 N/cm^2) as shown in fig. 39.

The next major step in the sequence was to purge both sides of the bellows by cycling the bellows through two complete cycles. The first half-cycle of the purge was accomplished by opening valve 28 to vent the bellows helium pressure while simultaneously opening valve 30 to purge helium into the liquid side. Then the majority of the helium on the pressurization side of the bellows was removed by evacuation. This was accomplished with a leak detector roughing pump connected to the system through valve 25. Evacuation continued until the pump exhaust noise reduced to a negligible level, indicating a pressure level in the range of 100 microns (0.0013 N/cm^2). Throughout the evacuating sequence the liquid side pressure was carefully monitored to assure that the allowable bellows differential pressure was not exceeded. This half-cycle required approximately 25 minutes (1500 sec) to complete. Pertinent pressure and valve operational data are included in fig. 39.

A second complete purge cycle was conducted in exactly the same manner as before, but was accomplished much more quickly than the first, probably because of the predominance of nitrogen in the gas being pumped rather than helium. Pertinent data are shown in fig. 39. At the end of this cycle, the gas on the liquid side of the bellows was predominantly helium, while the gas side was filled with almost pure nitrogen. Because of the late hour, the test was secured at this point instead of proceeding with the leak check.

By the time the leak check was conducted the following morning, the bellows assembly had warmed nearly to ambient temperature. The first step in the procedure was to vent the bellows down to approximately atmospheric pressure. The liquid side was first vented through valve 11 to approximately 13 psia (9 N/cm^2), then the gas side was vented through valve 28 to 15 psia (10.3 N/cm^2). Then test personnel entered the test cell, disconnected the pressurization system (heat exchanger) from the bellows inlet, and connected the vacuum hose (leading to the leak detector) in its place.

The leak detector, already in operation, was then used to evacuate the bellows. During evacuation, the liquid side pressure was carefully monitored, and valve 30 was actuated as necessary to maintain a slight positive gage pressure in the system. This is a somewhat critical operation with regard to exposure of the bellows to excessive differential pressure, but was accomplished with no difficulty whatsoever.

After several hours of pumping, the pressure level had become stable and it was possible to obtain a leak rate measurement. A leak rate only slightly above 10^{-8} scc He/sec was indicated, so the test was terminated. The system was secured by purging helium back into the pressurization side of the bellows (through valve 35) in preparation for the resumption of cycle testing.

E. ADDITIONAL SYSTEM MODIFICATIONS

Based on the experience gained in the previous tests, several modifications were made to the test apparatus before proceeding further with the cycle test program. The major modifications were the relocation of the drain from the LN₂ bath and the addition of heaters to accelerate the LN₂ boiloff.

The LN₂ vessel was removed from the system, dismantled, and reworked as follows:

- 1) A new drain hole was drilled and tapped in the bottom of the vessel, and the drain valve replumbed using larger fittings;
- 2) Several cracks in the seam between the bottom of the vessel and the barrel were repaired (rewelded);
- 3) Legs were welded on the bottom of the vessel to elevate it and provide clearance for the relocated plumbing;
- 4) The vessel was reinsulated with foam.

With regard to heaters, the following was accomplished:

- 1) A 660-watt wafer heater was attached to the short section of pipe that supports the bellows assembly in the bath. It was located to provide heat to boil off residual LN₂ in the bottom of the vessel, and warm the bellows assembly;
- 2) A 1000-watt tubular heater was located in the top (convex) dome of the bellows assembly to accelerate the boiloff of LN₂ trapped at this location;
- 3) Variacs were provided to control the power to each of the two heaters.

F. LN₂ CYCLES 16 THRU 32

The cycle tests conducted on 29 September 1970 required only a minimum of pretest operations. The cycle system supply tank still contained LN₂ from the previous series of tests, so it did not have to be filled. It was necessary only to set up the instrumentation, recheck the facility valves and regulator settings, and fill the LN₂ bath and jacketed lines.

These cycle tests employed essentially the same procedures as those used previously. In approximately 1 hr, after 17 cycles had been completed, the helium supply was depleted, and it was necessary to terminate the tests. The source of helium for these tests was the supply bottles located in the Cold Flow Laboratory, but the bottle valves had been shut off after charging the line to 2800 psig (1930 N/cm², g). It was thought that the entire series of tests could be conducted with the helium trapped in the line, but this did not prove to be the case. It was subsequently determined that the line volume is only about one-third the volume originally estimated, thereby explaining the helium shortage. Other than the problem experienced with the helium, the cycling tests were uneventful. Data obtained from this series of cycles are almost identical to those previously shown in fig. 38.

Draining of the LN₂ bath surrounding the bellows was completed in an elapsed time of only 30 minutes (1800 sec). This represented a considerable improvement over the previous drain operation (before modification of the drain) which required 45 minutes (2700 sec) and still only drained the level to within 2 in. (5 cm) of the tank bottom.

In the first few minutes of draining, the LN₂ level had dropped below the top of the (bellows) pressure vessel, and the top heater was turned on and operated for a short time at 50 volts. Operation appeared satisfactory, so the power was increased to 80 volts (~500 watts), a level that should be sufficient to evaporate the 9 lb (4.1 kg) of trapped LN₂ in 25 minutes (1500 sec). Actually, the dome was not quite dry in 30 minutes (1800 sec), so the heater was operated for an additional 30 minutes (1800 sec) at 50 volts (~200 watts).

As soon as draining of the bath was complete, the lower heater was turned on at a power level of 60 volts (~200 watts) to dry out the bottom of the vessel and hasten the warmup of the bellows. After 30 minutes (1800 sec) the top dome of the bellows assembly had warmed to 260°R (144°K), the bottom dome to 190°R (105°K).

During the warm-up period the bellows was pressurized with GN₂ through valve 32 as necessary to assure that the ΔP across the bellows was maintained within allowable limits. This was necessary because the helium supply normally provided through valve 29 had been exhausted.

Venting of the liquid side pressure down to atmospheric pressure in preparation for bellows purging was accomplished by a series of six pulses of valve 11 as shown in fig. 40. This was followed by venting the helium pressure down to approximately atmospheric through valve 28 (fig. 40).

The procedure followed for purging the bellows preparatory to leak checking was identical to that employed following the previous series of cycle tests. First the helium was evacuated from the bellows by a vacuum pump while simultaneously purging helium into the liquid side of the bellows at atmospheric pressure. Then the bellows was compressed by pressurizing it with GN_2 , while exhausting the gas mixture from the liquid side of the bellows. This entire cycle was then repeated, leaving the bellows in the compressed condition with almost pure GN_2 on the gas side and a mixture that was predominately helium on the liquid side. Pertinent pressure and temperature data during purging are also shown in fig. 40.

The leak check was also conducted in the same manner as previously, but the first attempt was unsuccessful. After pumping for 2 hr the helium count finally reached the 1000-scale on the leak detector, but it was evident that many more hours of pumping would be required before a valid leak measurement could be made. Therefore, the leak check was discontinued, and the apparatus secured for the night.

The reason for the slow pumpdown of the bellows is not precisely known, but it was probably the result of an inadequate vacuum purge of helium from the bellows. No pressure readings are made; only the exhaust noise of the vacuum pump is used as an indicator of the pressure level being attained. Figure 40 shows that the vacuum pump was operated at 0 psia (0 N/cm²) for less than 4 minutes (240 sec) during the first purge cycle, and only three minutes (180 sec) the second time.

The second attempt to conduct the leak check the following afternoon was successful. The same basic procedure was followed as before, but an additional purge of nitrogen into the bellows had reduced the helium concentration in the bellows by many orders of magnitude. Only 1½ hr of pumping was required to obtain a leak rate measurement of $<10^{-7}$ scc He/sec, so the test was terminated and the system secured.

When this series of tests was completed, it was decided to inspect the bellows for evidence of premature failure. The entire expulsion device was removed from the cycle test system, the lines capped to prevent contamination, and the bellows assembly removed from the pressure vessel to permit inspection. It was found that both end convolutions of the bellows were distorted for a distance of ~90 deg (1.57 radians) around the circumference. The convolutions on the flange-end had sustained the most damage (fig. 41); the one at the guide-ring end had "rolled-out" only a small amount. The two regions of distortion are not in the same axial plane. The points of maximum deflection are located approximately 100 deg (1.75 radians) from each other. The exact cause of this distortion was not and is still not known, but it was evident that this condition would have to be corrected before proceeding with the cycle tests.

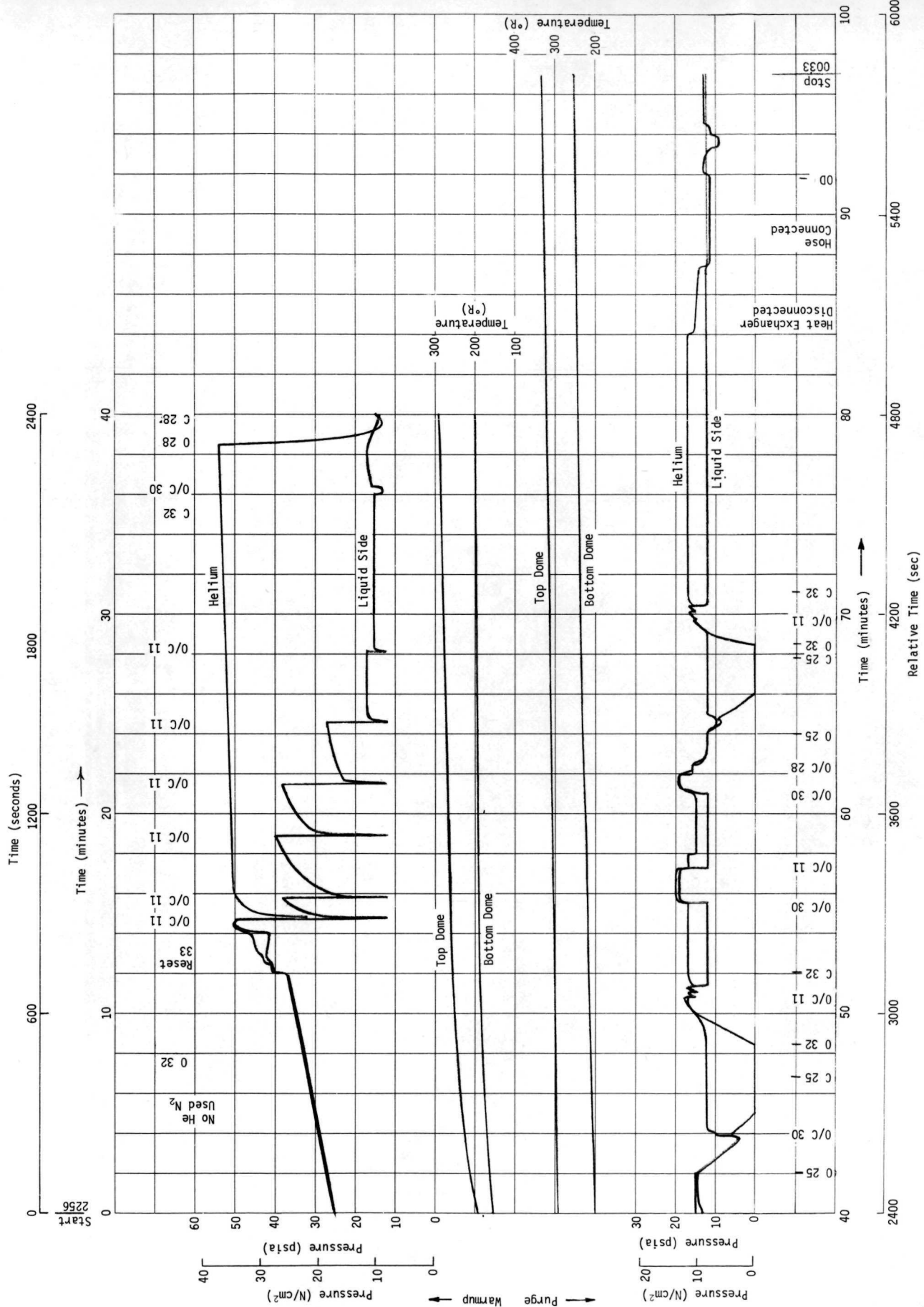


Figure 40 Warmup and Purge Events

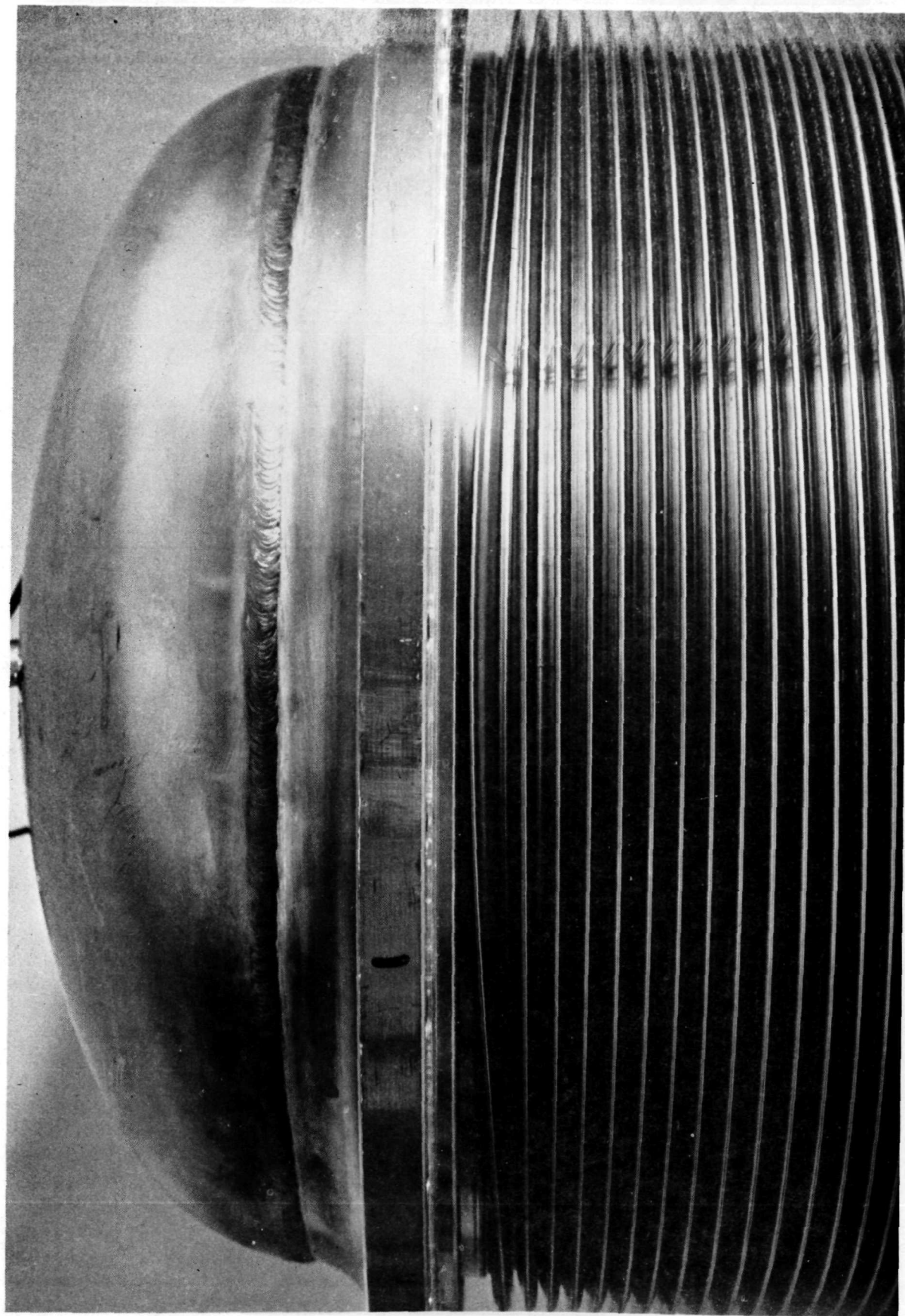


Figure 41 Distorted Convolution at Flange End

G. BELLOWS FAILURE ANALYSIS AND REPAIR

The most probable causes of the distortion were considered to be:

- 1) Excessive internal pressure, >15 psig (10.3 N/cm^2 , g), during testing, causing squirming and possibly permanent distortion;
- 2) Progressive distortion possibly resulting from initial distortion of the bellows neck during proof testing to 265 psig (183 N/cm^2 , g);
- 3) Design or fabrication deficiencies that might result in eccentricity, binding of moving parts, improper seating of domes, etc.

None of the above can be positively identified as the cause based on the available data. Pressure data are recorded continuously throughout cycling, purging and leak checking, and none of these data indicate any abnormal conditions. However, the bellows assembly is installed in the system for long periods of time during which data are not recorded, and it is possible that unfavorable pressures were inadvertently imposed on the bellows during this time. One possibility is a temporary loss of electrical power or pneumatics during the night.

Application of excessive external pressure during cycling is not a realistic possibility because the system pressure had never been allowed to reach even 100 psig (69 N/cm^2 , g) in any of the tests. However, the proof test does produce some distortion of the bellows neck which conceivably could contribute to further distortion during repeated cycling. The bellows neck, originally a cylinder, is deformed into a shallow conical shape during proof testing, as was shown in fig. 24.

With regard to design or fabrication defects, it can only be said that this is not believed to be a factor. The various steps in the fabrication sequence were carefully controlled, and it does not appear likely that an unfavorable accumulation of tolerances occurred which would be detrimental to the proper operation of the bellows. The assembly had been subjected to a number of cycles in the exercise fixture while the operation was carefully observed, and there was no evidence whatsoever of binding, sticking or any other unsatisfactory characteristics.

To obtain the maximum benefit from the experiences of DK-Aerospace, the bellows was taken there for evaluation on 6 October. DK-Aerospace personnel were in general agreement with the possible causes proposed by Martin Marietta, but were unable to identify a specific cause. They were very successful, however, in eliminating essentially all of the distortion in the bellows. This was done by skilled technicians using special tooling. The convolutions were first gradually reshaped by repeated hand forming with a Teflon tool. Then the bellows was cycled several times while forcing the convolutions to seat on special nylon dies. The convolutions were not restored to exactly their original contour, but the remaining distortion was hardly noticeable.

To preclude further distortion of this nature, it was decided to fabricate a set of support rings for each end of the bellows. The design of the ring for the flange end of the assembly is shown in fig. 42. The other is similar, but is contoured to match the convolution at the guide-ring end. After installation of the rings, the bellows was cycled several times while mounted in the exercise fixture, but the convolutions at the guide-ring end did not appear to seat properly against the support ring. Finally, the ring was removed. Operation of the bellows appeared to be entirely normal throughout the entire stroke without the ring, so it was not reinstalled. The bellows was then reassembled in the pressure vessel in preparation for resumption of cycle testing.

H. LN_2 CYCLES 33 THRU 74

This was the third series of cycle tests originally planned. Actually only 42 cycles were conducted instead of 50, because the bellows had been subjected to an additional 8 to 10 cycles during reforming of the convolutions and various purging operations. The basic procedures for cycling were similar to those followed in previous tests, but several parameters were varied to determine their effects on cycle characteristics:

- 1) Pressure regulator 12 was set at two different values;
- 2) Sequencing of valves 16 and 10 (supply tank pressurization and venting) was varied from test to test.

Within an hour after test operations were begun, the facility valves and regulators had been set up, the LN_2 dewar connected, the baths filled and jacket cooldown initiated, and data recording equipment checked out. The supply tank still was 80% full of LN_2 from the previous tests.

The first 10 cycles were conducted at a relatively low expulsion pressure, ~ 35 psia (24 N/cm^2). Also, they were characterized by a somewhat simplified procedure that omitted the operation of valves 16 and 10 to pressurize and vent the supply tank. The bellows was filled by venting the helium pressure through valve 28; expulsion was effected by pressurizing the bellows through valve 29. The entire cycle consumed only about $2\frac{1}{2}$ minutes (150 sec), but was poor due to considerable vaporization and recondensation within the system. The flowmeter oscillated considerably, and the integrated flowrate could not be made to correlate with the bellows displacement because of the two-phase flow occurring. The bellows, however, was subjected to the same temperature, pressure loading, and stresses as in the previous cycles.

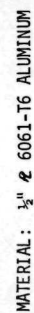


Figure 42 Support Ring for Flange-End Convolution

Upon completion of the tenth cycle, valve 12 was reset to a pressure of 50 psia (34.5 N/cm^2), and an additional 20 cycles were conducted. The first three were conducted in the same manner as before, without operating valve 16 or 10. Several positions of valve 7 were tried from 3% to 100%, but the results were still poor. Subsequently, the procedure was modified to pressurize the supply tank (through valve 16) during the fill portion of the cycle, and venting (through valve 10) near the end of the expulsion cycle. The result was a relatively "clean" cycle with little oscillation of the flowmeter, and an integrated flowrate that correlated well with the bellows displacement of 4.6 gallons (0.017 m^3). Several of these cycles are reproduced in fig. 43. Note that the bellows apparently seats approximately one minute after the start of fill (evidenced by the drop in helium pressure), but flow continues for another 30 minutes (1800 sec) as vapor is condensed within the bellows. Expulsion is characterized by two peaks in the flowrate, the second one resulting from an abrupt increase in flow when the supply tank is vented to 23 psia (15.9 N/cm^2).

Following cycle 62, the pressure regulator (valve 12) was reset again to a lower pressure, 35 psia (24 N/cm^2), and cycling resumed using the same procedure as for the previous 20 cycles. Valve 7 was set at openings of 5, $7\frac{1}{2}$, 10, and 15% for cycles 63 through 67 to determine its effects. Some cycles were conducted with a single venting of the supply tank, others employed a double vent.

At the end of cycle 70, the pressurization valve (12) was reset for 50 psia (34.5 N/cm^2), and four additional cycles were conducted to conclude this series of tests.

The warm-up sequence was the same as in the previous series of tests, and proceeded as shown in fig. 44. In 70 minutes (4200 sec), the upper dome had warmed to nearly 240°R (133°K), and the lower dome to 162°R (90°K). Note that the vapor pressure of nitrogen at 162°R (90°K) is 52 psia (36 N/cm^2), a value that compares very favorably with the bellows liquid-side pressure being measured at that time, 54 psia (37 N/cm^2).

Venting of the liquid-side pressure was accomplished in a series of 18 pulses of the vent valve as shown in fig. 44. There was no tendency for the pressure to spike to high values as had been experienced in some previous tests when the bellows had not been adequately warmed. Throughout this vent sequence the bellows remained in the compressed condition as a result of a helium pressure of ~ 65 psia (44.8 N/cm^2) being maintained on the gas side.

The purge sequence was identical to that used following the previous series of cycle tests (see fig. 40), except that the evacuation was continued for a somewhat longer period of time to assure an adequate purge. Both evacuations were allowed to continue for 12 minutes (720 sec), then the test was secured for the night.

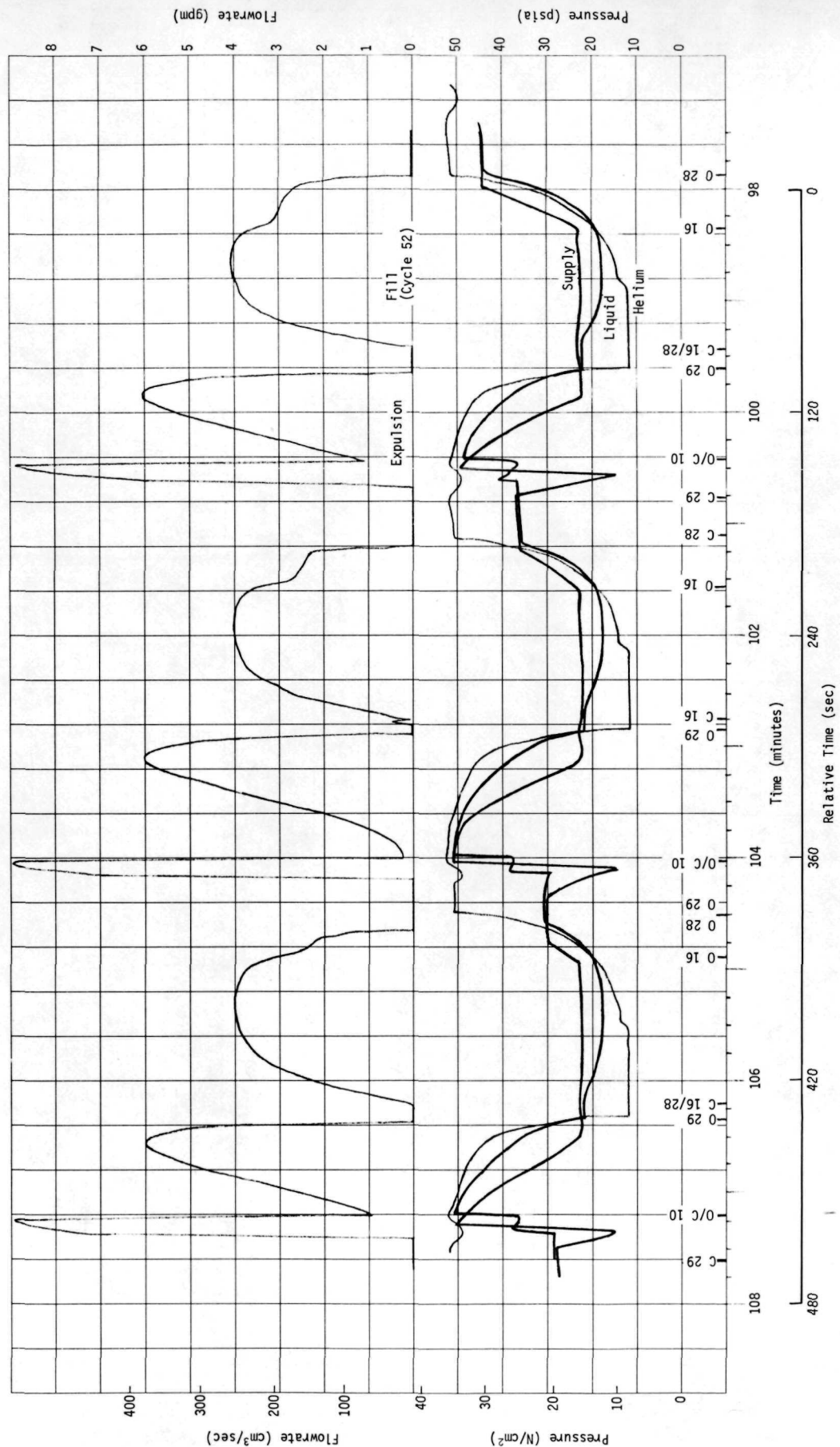


Figure 43 Improved F111/Expulsion Cycles (10/22/70)

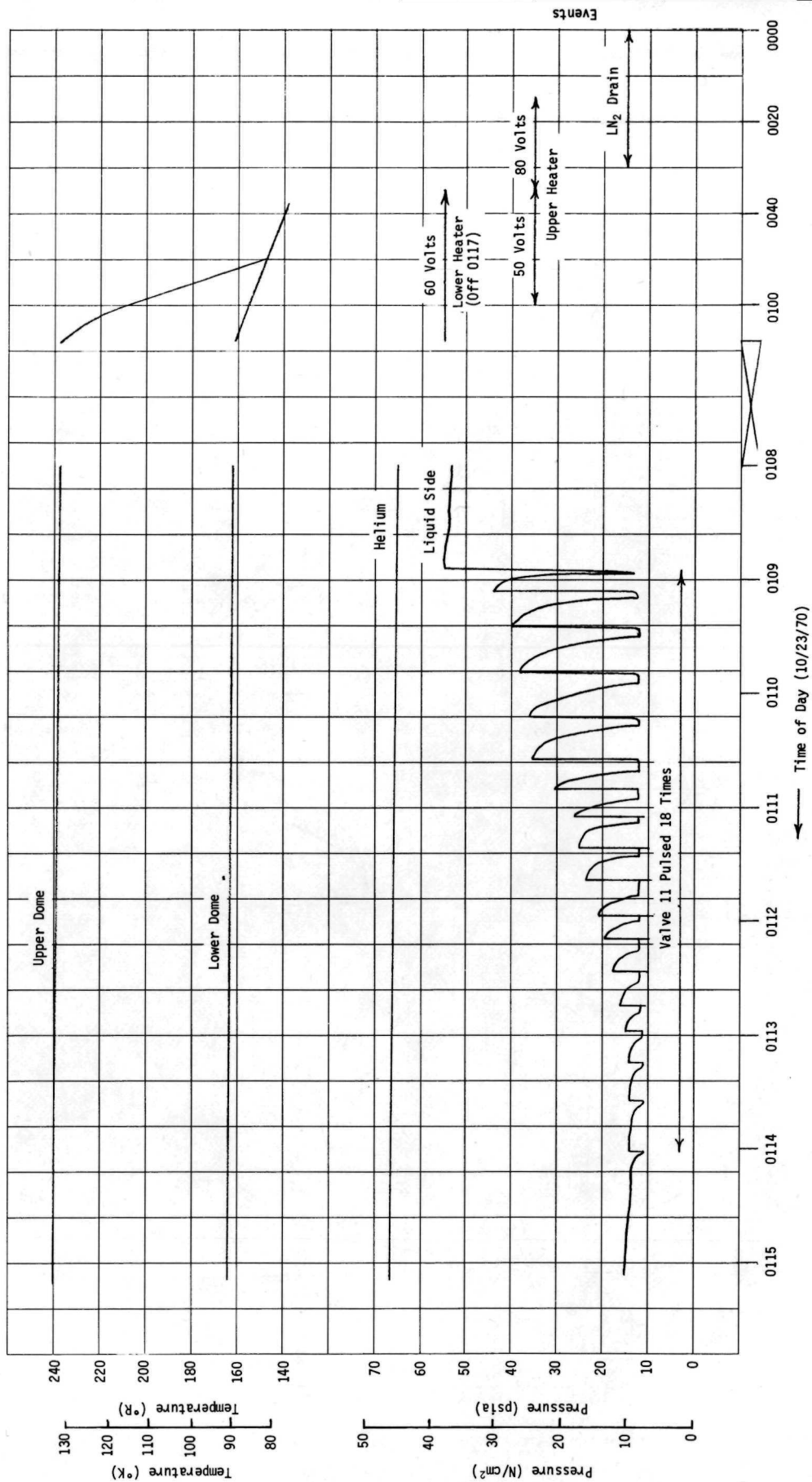


Figure 44 Warmup Following Cycle Tests (10/22/70)

The leak check was conducted after the bellows assembly had warmed over the weekend. The initial steps of the procedure were the same as those employed previously. The leak detector was connected directly to the bellows assembly, the helium was purged into the liquid side of the bellows as the gas side was evacuated with the detector. After only 30 minutes (1800 sec) of pumping, a reading $<10^{-7}$ scc He/sec was obtained so the test was terminated. Since it was planned to immediately disassemble the bellows, air was bled directly into the bellows (gas side) instead of employing the normal helium purge.

The bellows assembly was then removed from the test system, the lines capped to prevent contamination, and the bellows assembly disassembled and inspected. No evidence of damage was noted. The convolutions appeared to be in exactly the same condition as they were before the tests (see fig. 45). The convolution at the guide-ring end showed no tendency to "roll-over" even though it had remained unsupported throughout this series of cycle tests.

I. LN_2 CYCLES 75 THRU 171

This series of cycles was conducted primarily to accumulate additional cycles toward the eventual determination of bellows cycle life. No significant experimenting was done with the test procedures previously developed.

Pretest operations were completed in approximately 45 minutes (2700 sec). For the initial cycles valve 12, which controls the expulsion pressure, was set for 30 psig (20.7 N/cm^2 , g); the flow throttling valve (7) was set 5% open. The valve sequence was identical to that used for the majority of the cycles conducted on 22 October; i.e., the supply tank was pressurized through valve 16 during the fill portion of the cycle, and the supply tank was vented momentarily through valve 10 near the end of the expulsion cycle.

As usual the first few cycles were poor as evidenced by long fill and expulsion times, and excessive flowmeter oscillations. Actually, the first few cycles accomplish the final cooldown of the system (including bellows), and therefore, involve a considerable amount of two-phase flow. The flowmeter record for cycle 76 (a typical "poor" cycle) is reproduced in fig. 46.

Valve 7 was opened to 10% upon completion of cycle 76, then opened to 15% upon completion of cycle 80. Cycles 79 and 80 were good, though the fill and expulsion flowrates were low, and the elapsed times relatively long. Cycle 81, and subsequent cycles, were "normal."



Figure 45 Bellows Assembly 5 After Cycle 74

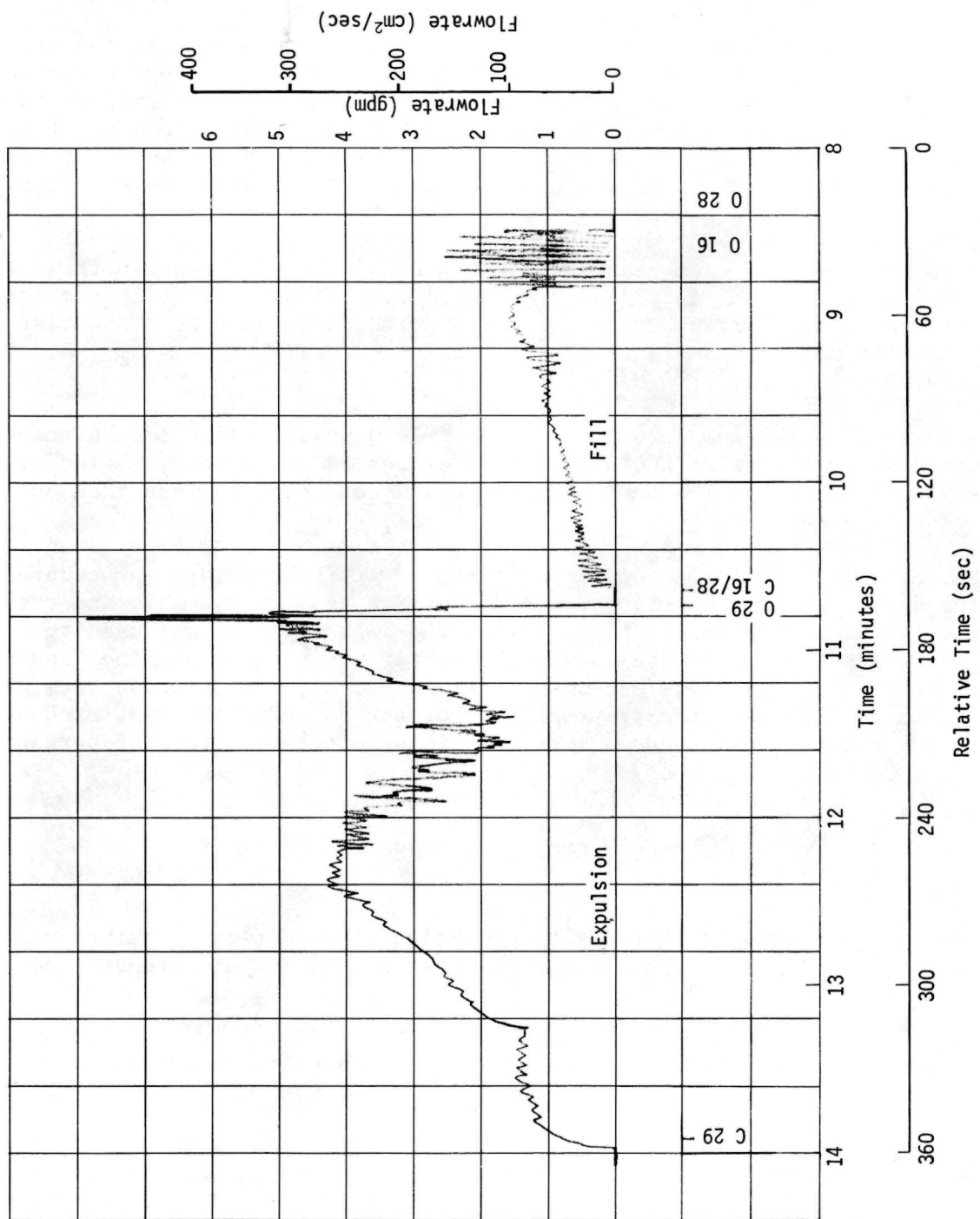


Figure 46 Flowrate Data for Cycle 76 (Inadequate Cooldown)

After completing 25 cycles, pressure regulator 12 was reset to 25 psig (17.2 N/cm^2 , g) to lower the expulsion pressure and thereby reduce the helium consumption. This second group of 25 cycles was completed in 75 minutes (4500 sec) for an average cycle time of 3 minutes (180 sec).

The next 38 cycles were conducted in exactly the same manner as the previous 25 cycles. Upon completion of cycle 162, the helium supply valve was turned off and the remaining cycles conducted using the helium that was trapped in the line. The helium supply pressure dropped from 920 psig (635 N/cm^2 , g) at the end of cycle 162 to 60 psig (41.4 N/cm^2 , g) following cycle 171 when the test was terminated. This is a pressure drop of less than 100 psig (69 N/cm^2 , g) per cycle, or a computed consumption of about 8 scf (226 m^3) helium per cycle.

Warmup followed the same sequence as before. The final steps in the sequence were to vent the liquid-side pressure down to approximately atmospheric by cycling valve 11, and then vent the gas side through valve 28. The test was secured for the day with the gas-side pressure at 25 psia (17.2 N/cm^2) and the liquid side at 12.5 psia (8.6 N/cm^2).

The purge sequence was accomplished the following day using the "standard" procedure. The gas side of the bellows was evacuated twice for a period of 12 minutes (720 sec) each. The entire sequence was completed in less than an hour.

The leak check also proceeded in accordance with the standard procedure. First the heat exchanger was disconnected from the bellows assembly and the leak detector connected in its place. Then the leak detector was used to evacuate the gas side of the bellows while helium was purged into the liquid side. A reading $<10^{-7}$ scc He/sec was quickly obtained, and the test terminated. Helium was bled back into the pressure side of the bellows, the heat exchanger reconnected, and the test secured less than $1\frac{1}{2}$ hr after the start of purging.

J. LN_2 CYCLES 172 THRU 265

A primary objective of this series of cycles (in addition to gathering data on cycle life) was to evolve optimum cycle test procedures with regard to:

- 1) Expulsion at higher pressure;
- 2) Eliminating, or at least reducing the flowrate spike that usually occurred near the end of the expulsion cycle when the supply tank was vented.

The expulsion pressure was changed several times during the tests to cover a wide range of conditions, and the procedure for venting the supply tank was also varied.

Pretest operations were completed within 1 hr. For the initial cycles, valve 12 was set for 25 psig (17.2 N/cm^2 , g), the throttling valve (7) was set at 15% open.

As usual, the first few cycles proceeded relatively slowly and were characterized by flowrate spikes that are indicative of two-phase flow. By the time the third cycle was completed, however, cooldown was essentially completed and the cycles approached normal. Data for a typical cycle (181) are presented in fig. 47.

Forty cycles were completed in 75 minutes (4500 sec), then testing was interrupted to replace the supply tank pressure transducer. A 0-100 psia (0-69 N/cm^2) transducer was installed in place of the 0-50 psia (0-34.5 N/cm^2) transducer so that the system could be operated at high pressures without danger of transducer damage. At the same time, the instrumentation was recalibrated and the strip chart recorder respanned from 0-50 psia (0-34.5 N/cm^2) to 0-100 psia (0-69 N/cm^2).

Three additional cycles were conducted at the low expulsion pressure, then regulator 12 was reset to 60 psig (41.4 N/cm^2 , g). For subsequent cycles, however, a somewhat different procedure was employed. During the fill portion of the cycle valve 7 was left open to 15% the same as for previous cycles, but for expulsion the valve was set at a smaller opening in an attempt to maintain the flowrate at 5 gpm ($315 \text{ cm}^3/\text{sec}$) maximum. A number of different valve openings ranging from $+2\frac{1}{2}\%$ to -1% (as read on the controller) were tried during the next several cycles. In addition, the cycle sequence was varied in two other respects:

- 1) During bellows fill valve 15 was left closed until the supply tank pressure dropped to ~ 20 psia (13.8 N/cm^2) to assure that there would be no backflow through the regulator (a critical consideration for fluorine cycle tests);
- 2) Near the end of expulsion vent valve 10 was cycled a number of times to prevent the supply tank pressure from exceeding 50 psia (34.5 N/cm^2), and at the same time to achieve a more uniform flowrate.

Data from two representative cycles of this series (215 and 217) are presented in fig. 47. The first of these employed only a single cycle of valve 10 (and produced the familiar flowrate spike); the second employed two short pulses that resulted in an improved flowrate characteristic. Although the flowrate/time curves varied somewhat from test to test (particularly, the expulsion flowrates), the integrated flowrates are all in the range of 4.6 ± 0.2 gallons ($0.017 \pm 0.0007 \text{ m}^3$), indicating only a very minimum amount of two-phase flow.

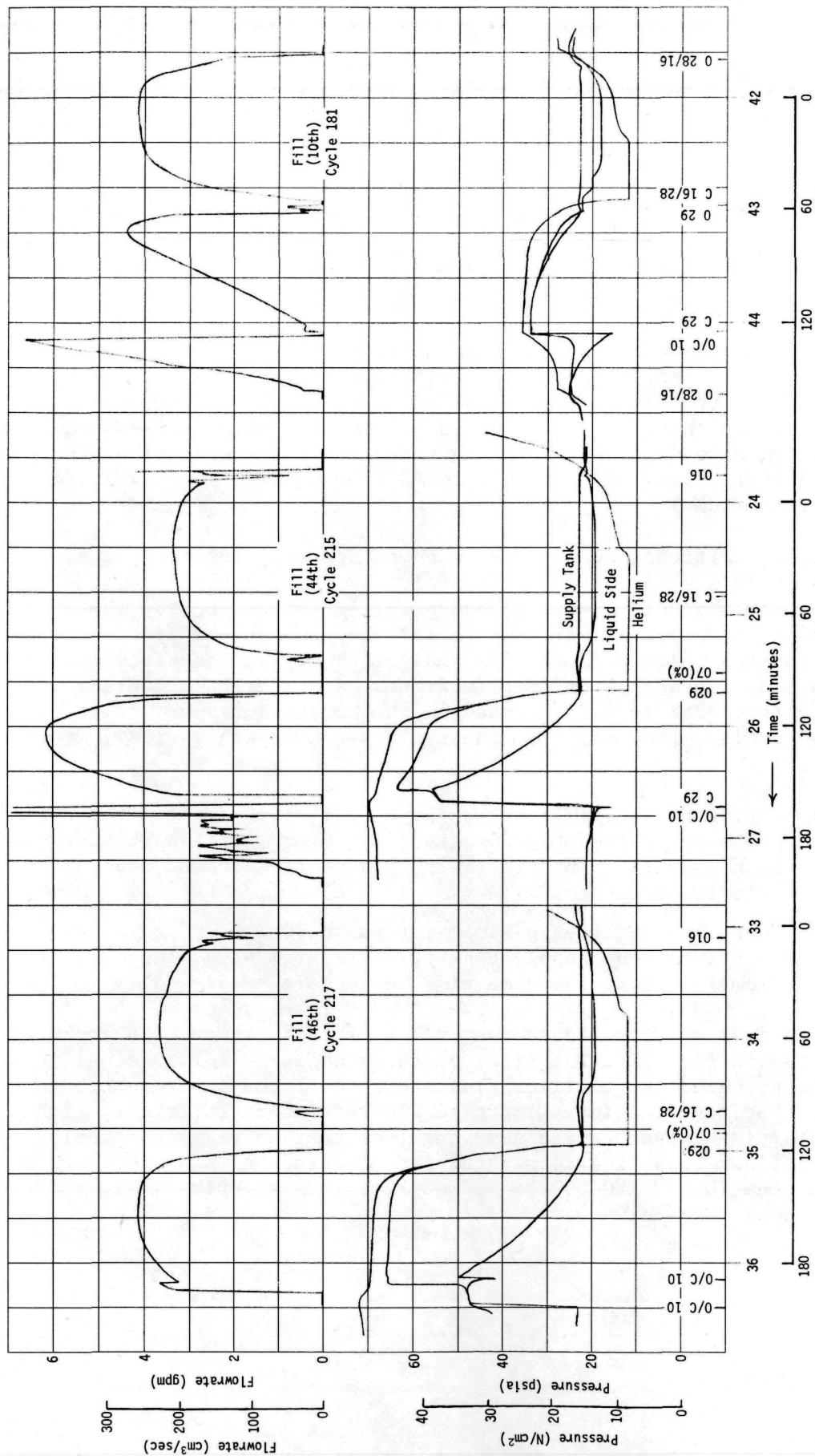


Figure 47 Typical LN₂ Cycle Test Data (10/30/70)

Upon completion of ten cycles at the higher expulsion pressure, the regulator was reset to 25 psig (17.2 N/cm^2 , g) to conserve helium during the next group of cycles. This series of 35 cycles was similar to the initial 40 cycles, but instead of a single vent of the supply tank near the end of expulsion, a series of vents was employed. Data for a typical cycle in this group (252) is presented in fig. 48. The fill portion of the cycle is almost identical to that for cycle 181 (fig. 47), but the expulsion flowrate is much improved as a result of the 10 short pulses of valve 10.

For the next four cycles (256 thru 259), the helium regulator was set to produce an expulsion pressure of 100 psia (69 N/cm^2), the highest pressure attempted to this point. The sequence for these cycles was much the same as that used for cycles 215 and 217 shown in fig. 47. The throttling valve (7) was 15% open during fill, and was nearly closed for expulsion. Data for a typical cycle is presented in fig. 49. This particular cycle employed a throttling valve opening of -2% during expulsion, and required only one pulse of vent valve 10 to obtain a uniform expulsion flowrate.

Again to conserve helium, the helium regulator was reset to a low pressure, 30 psig (20.7 N/cm^2 , g) for the remaining six cycles. These were completed before 2:30 PM, an elapsed time of approximately 6 hr (21,600 sec) for the 94 cycles. The characteristics of this last group of cycles were essentially duplicates of that shown in fig. 48 (cycle 252).

Warmup was accomplished by the standard procedure, and was completed in approximately an hour. The test was then secured for the day with the bellows in the compressed condition and all valves closed.

The purge sequence was begun the following Monday, and proceeded exactly as in previous tests. Helium was purged into the liquid system by sequential operation of valves 30 and 28 until the bellows was fully extended, then the gas side was evacuated. This was followed by repressurization through valve 29 (and venting through valve 11) until the bellows was compressed. This cycle was repeated, with the purge sequence completed in 45 minutes.

The leak-check procedure proceeded as in previous tests, but it was not possible to obtain a leak-rate measurement. After continued operation of the rough pump for 2 hr without achieving a low enough pressure to permit activation of the diffusion pump, it was evident that there was a large leak some place in the bellows assembly. Consequently, the test was secured and the bellows assembly removed from the test system for inspection.

To permit visual inspection of the bellows, the bolts were removed from the flanged section, and the bellows assembly withdrawn from the pressure vessel. Visual inspection revealed no discrepancies. The bellows looked exactly as it had the last time it was inspected on 26 October 1970 when the first 74 cycles were completed (fig. 45). There was no evidence of progressive distortion of the end convolutions.

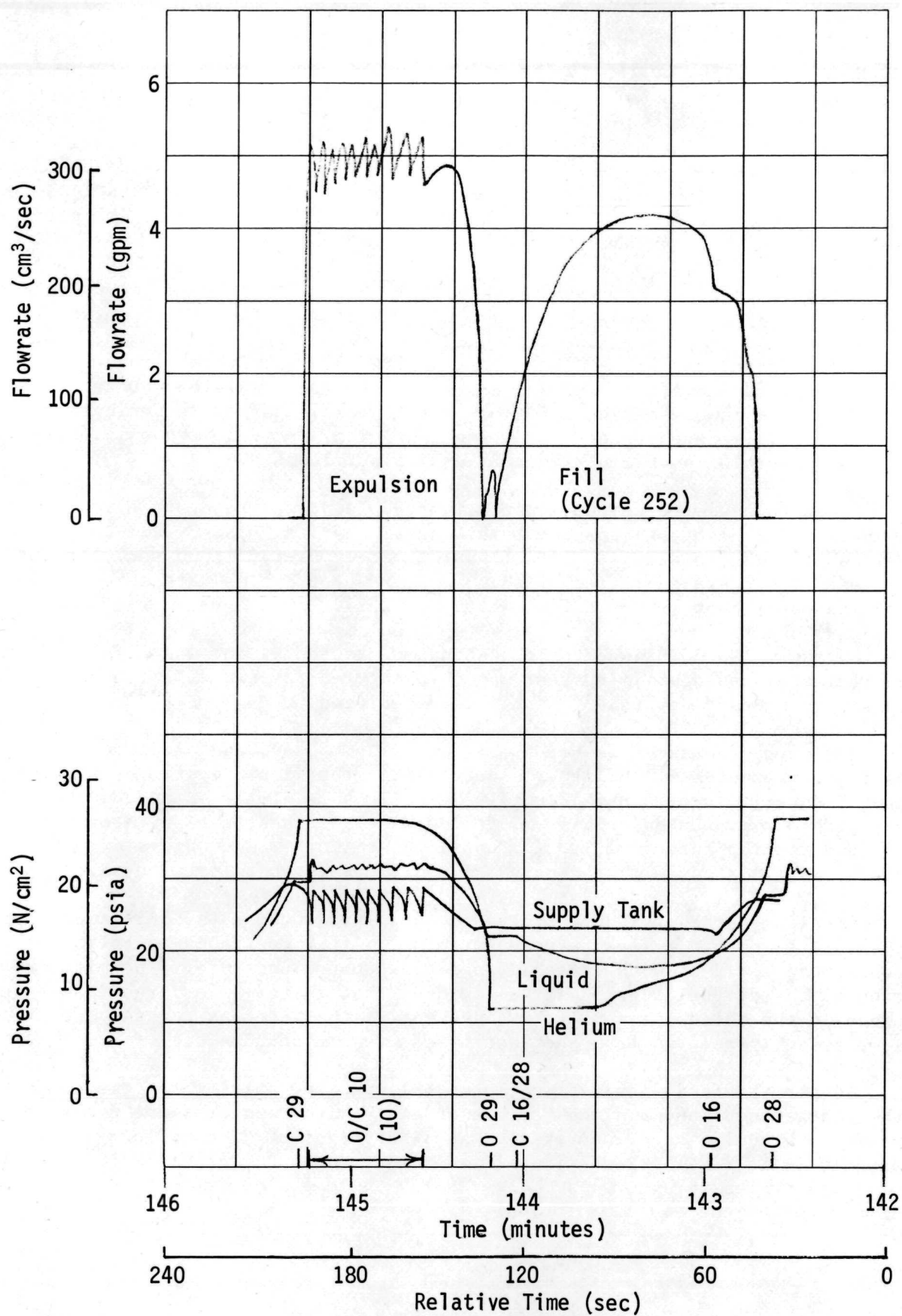


Figure 48 Data for LN_2 Cycle 252 (10/30/70)

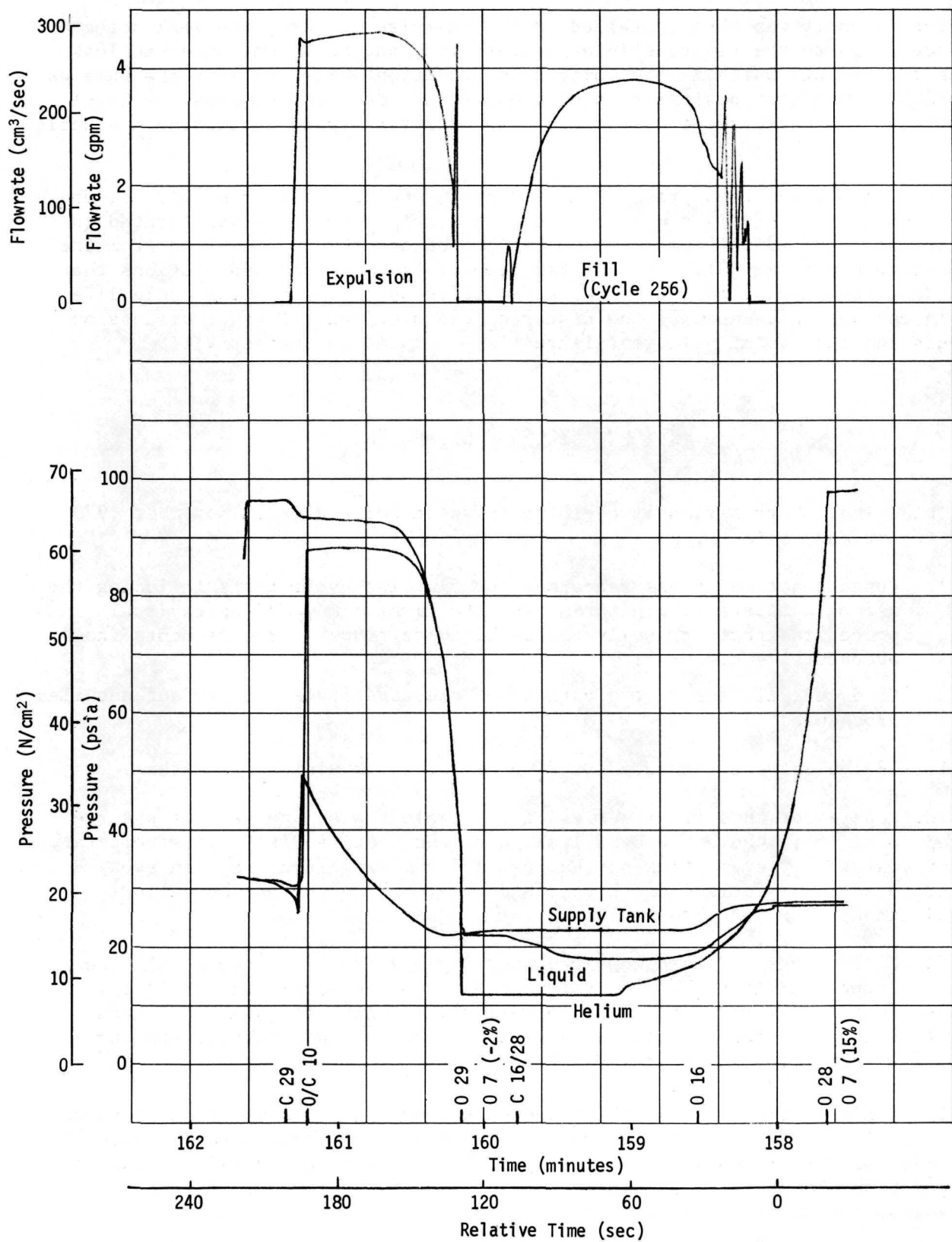


Figure 49 Data for LN₂ Cycle 256 (10/30/70)

The assembly was then installed in the exercise fixture, the leak detector was connected to the fluorine inlet/outlet line, and an attempt made to leak check the bellows while in the compressed condition. Results were the same as before. It was not possible to pump the assembly down to the pressure level required for a measurement by the CEC leak detector, again indicating a sizable leak.

The bellows was then pressurized internally to 8 psig (5.5 N/cm^2 , g), and all welds were carefully bubble checked. A single large leak was located in one of the longitudinal seams of the bellows on the 18th convolution from the guide-ring end (fig. 50). This is far removed from the end convolutions that were distorted during the early tests, so it is unlikely that the cycle life was in any way influenced by the distorted convolutions. Further discussion of this and subsequent bellows failures is presented in Chapter VIII.

K. LN_2 CYCLES 266 THRU 283

This final short series of cycle tests was conducted on 13 November 1970 with two primary objectives:

- 1) Conduct a final dress rehearsal for fluorine cycle tests including the use of complete TV monitoring for the first time, and operational procedures that are fully compatible with fluorine requirements (no procedural shortcuts).
- 2) Conduct cycle tests at a variety of pressure levels to perfect detailed procedures.

In all, 18 cycles were conducted at five different expulsion pressures.

To prepare for this final series of LN_2 cycle tests, the bellows was repaired to minimize the effects of leakage on the test results. This temporary repair was made by evacuating the bellows and applying "Loctite," an epoxy resin, to seal the fatigue crack that had developed in one of the bellows convolutions.

Since two weeks had elapsed since the previous series of tests, all the LN_2 had evaporated from the supply tank and it was necessary to refill it. This plus the other usual precycle operations, required slightly more than 2 hr to complete. For the initial series of tests the helium pressure regulator (12) was set at 25 psig (17.2 N/cm^2 , g).

The basic procedure for filling and expulsion was the same as in previous tests. Filling was initiated by venting the helium pressure through valve 28, and continued by pressurization of the supply tank through valve 16. Expulsion was performed by repressurization of the bellows through valve 29, the repeated venting of the supply tank through valve 10.

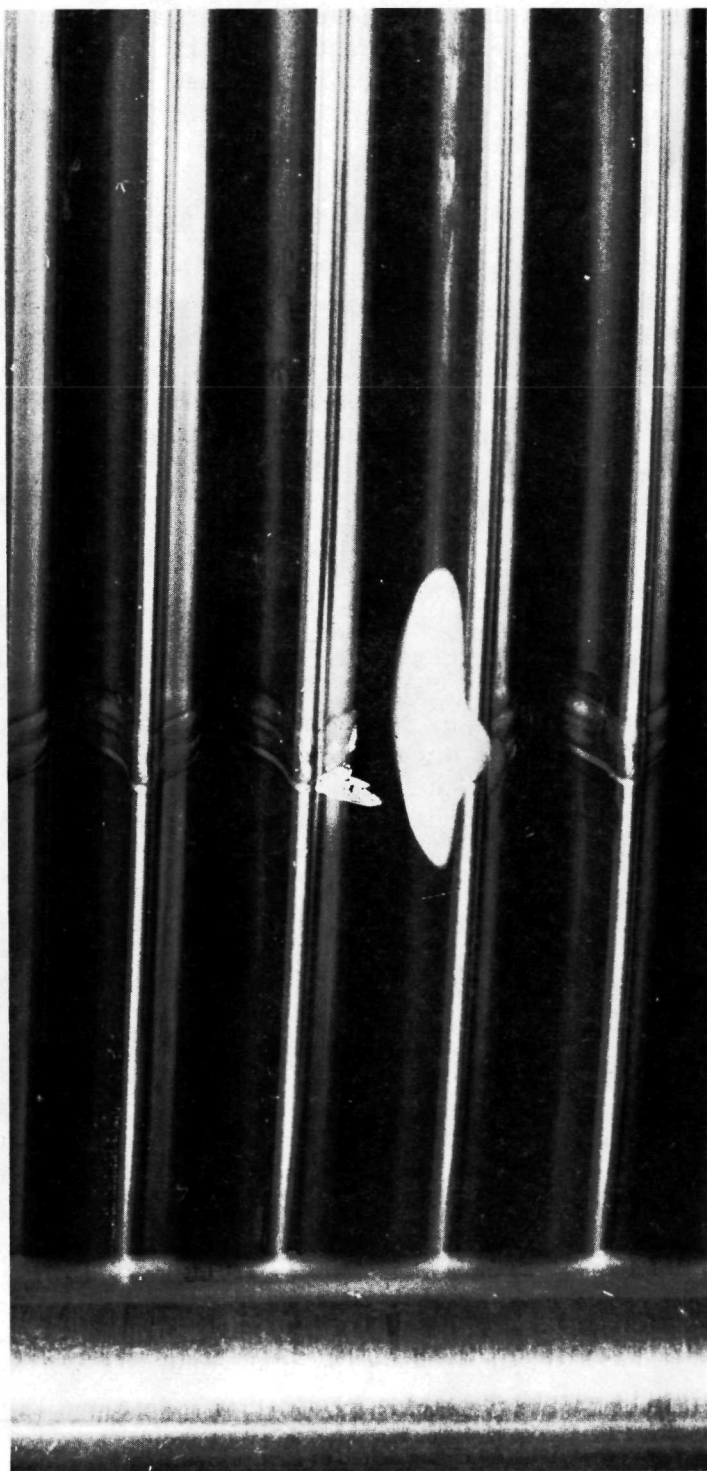


Figure 50 Cluster of Bubbles from Crack in Bellows

As usual, the first few cycles were characterized by unsteady flow resulting from residual gas in the system and incomplete cooldown. After completing three cycles the major portion of the gas had been eliminated from the system, and the flowmeter indicated only a liquid-phase flow. Data from a typical cycle (271) is presented in fig. 51. The flowrate variations occurring during the fill portion of the cycle are the result of repeated pulsing of the supply tank pressurization valve (16); the variations during expulsion result from cycling the supply tank vent valve (10).

Within 45 minutes (2700 sec) seven cycles had been completed, and pressure regulator 12 was reset from 25 to 50 psig (17.2 to 34.5 N/cm², g). Three cycles were then conducted at this higher expulsion pressure. The procedure was the same as before, except that it was necessary to reset throttling valve 7 for each half-cycle. The bellows was always filled with the valve 15% open; expulsion was accomplished with the valve more nearly closed. The first expulsion was conducted with the valve set at 0% open, resulting in an expulsion flowrate of only 2½ gpm (158 cm³/sec). For the second and third cycles of the series the valve was set 2% open and resulted in a peak flowrate of 5½ gpm (347 cm³/sec). The data for one of these latter cycles (274) are also presented in fig. 51.

Following cycle 275 the regulator was reset to 75 psig (51.7 N/cm², g), and three more cycles were conducted. The same procedure was used as before, except that slightly different settings were used for the throttling valve during expulsion. The valve was initially set at -1% open, but the resulting flowrate was considerably lower than desired, ~1½ gpm (95 cm³/sec). Consequently, the valve was readjusted to 0% and an acceptable flowrate of 4 gpm (252 cm³/sec) was obtained for the remainder of the expulsion. This opening was then also used for the other two cycles conducted. Data for a typical cycle (278) are shown in fig. 52.

Following cycle 278, the regulator was reset to a still higher pressure, 100 psig (69 N/cm², g) and two cycles conducted. A throttle valve setting of 0% was used for expulsion during both cycles. Typical data (cycle 279) are presented in fig. 53.

The final four cycles were conducted with the helium pressure regulator set at 125 psig (86 N/cm², g). For the first of these the throttling valve was set at -2% during expulsion, resulting in a flowrate of about 3½ gpm (221 cm³/sec). For the other cycles the valve was set at a slightly larger opening and the expulsion flowrate increased to approximately ~5 gpm (315 cm³/sec). Data for cycle 281 are presented in fig. 54.

Warmup of the bellows assembly and vent down of the liquid-side pressure in preparation for leak checking proceeded in the usual manner and were completed in 80 minutes (4800 sec). Then the purging sequence was initiated.

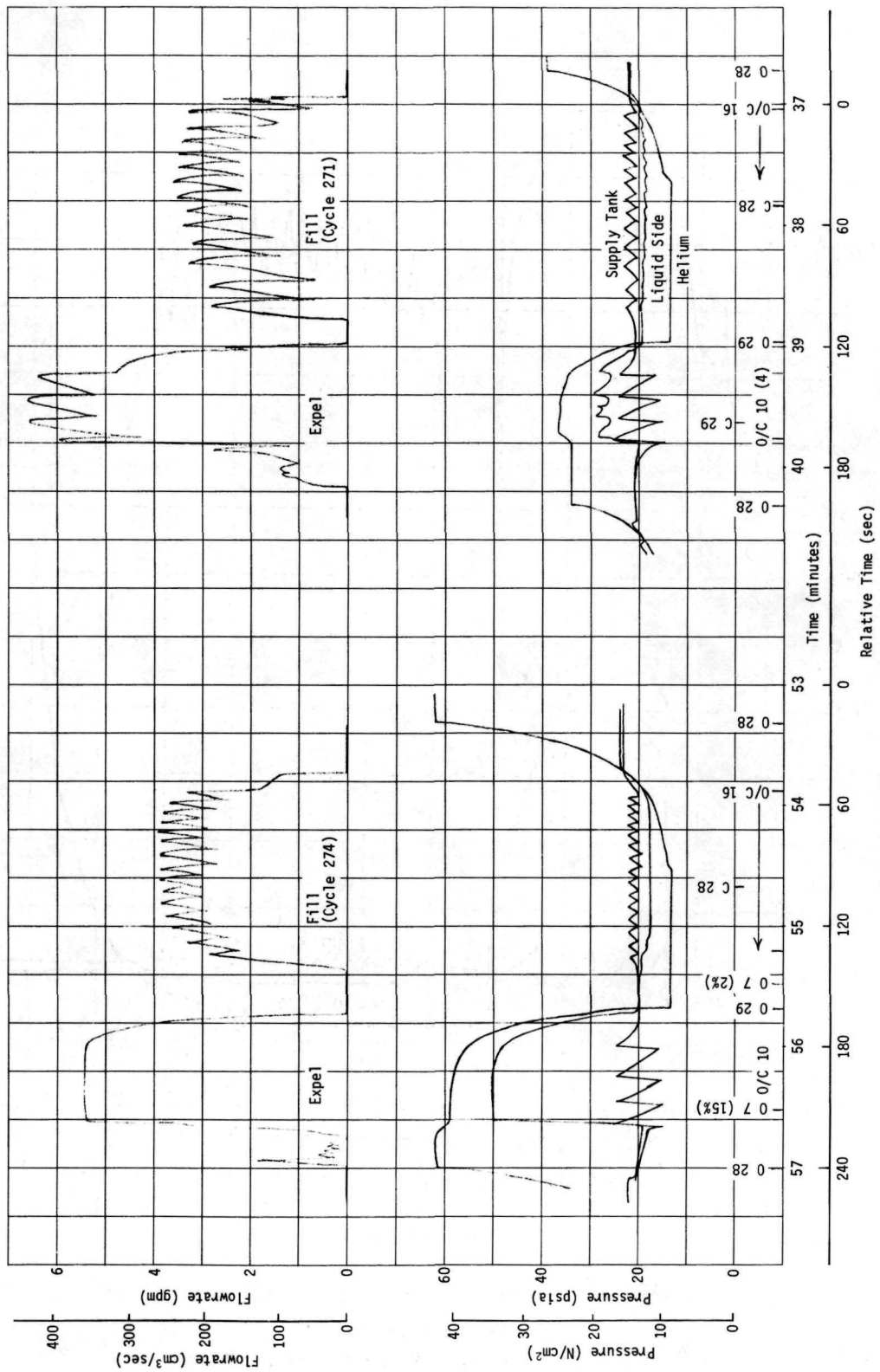


Figure 51 Data for LN₂ Cycles 271 and 274 (11/13/70)

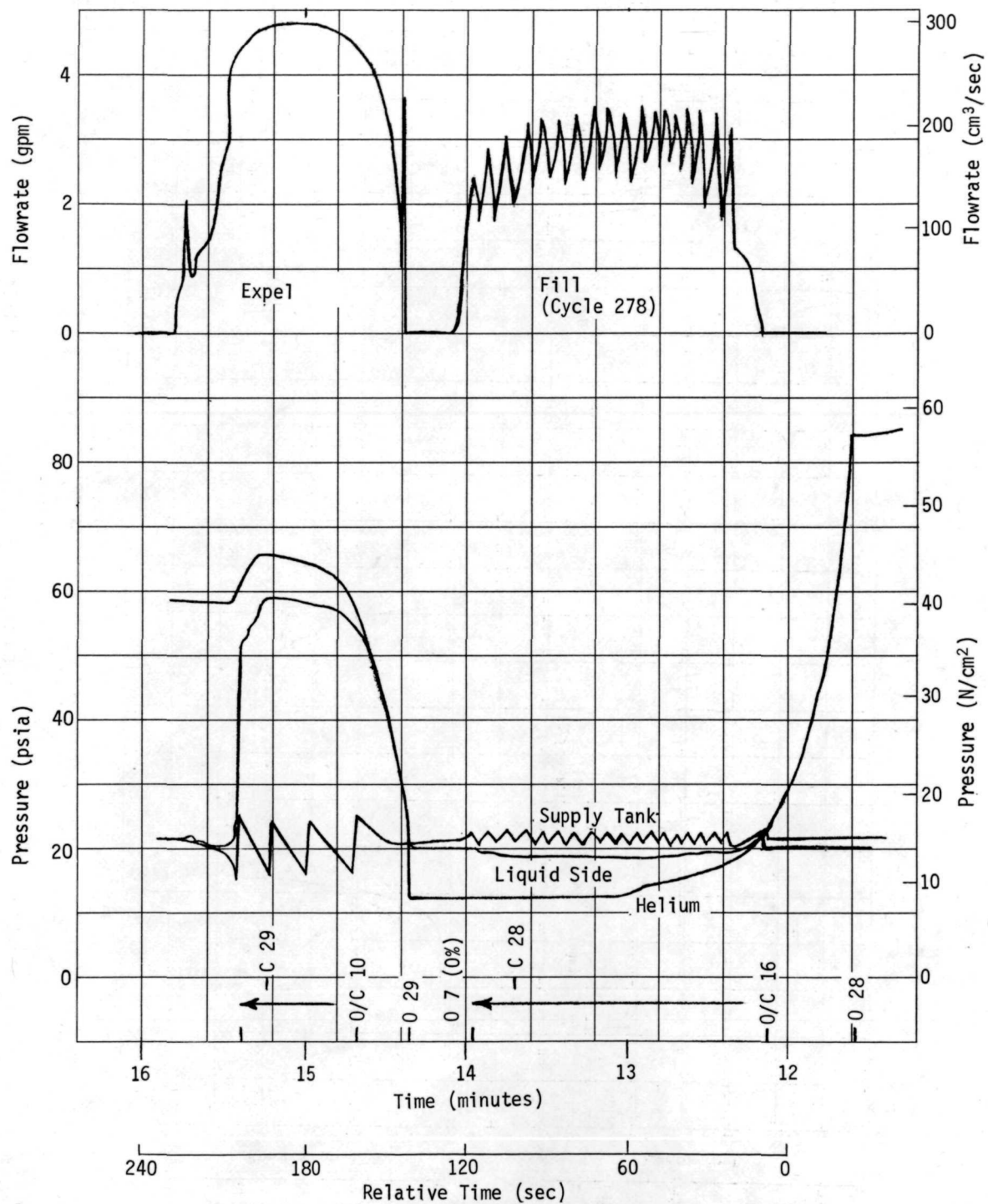


Figure 52 Data for LN₂ Cycle 278 (11/13/70)

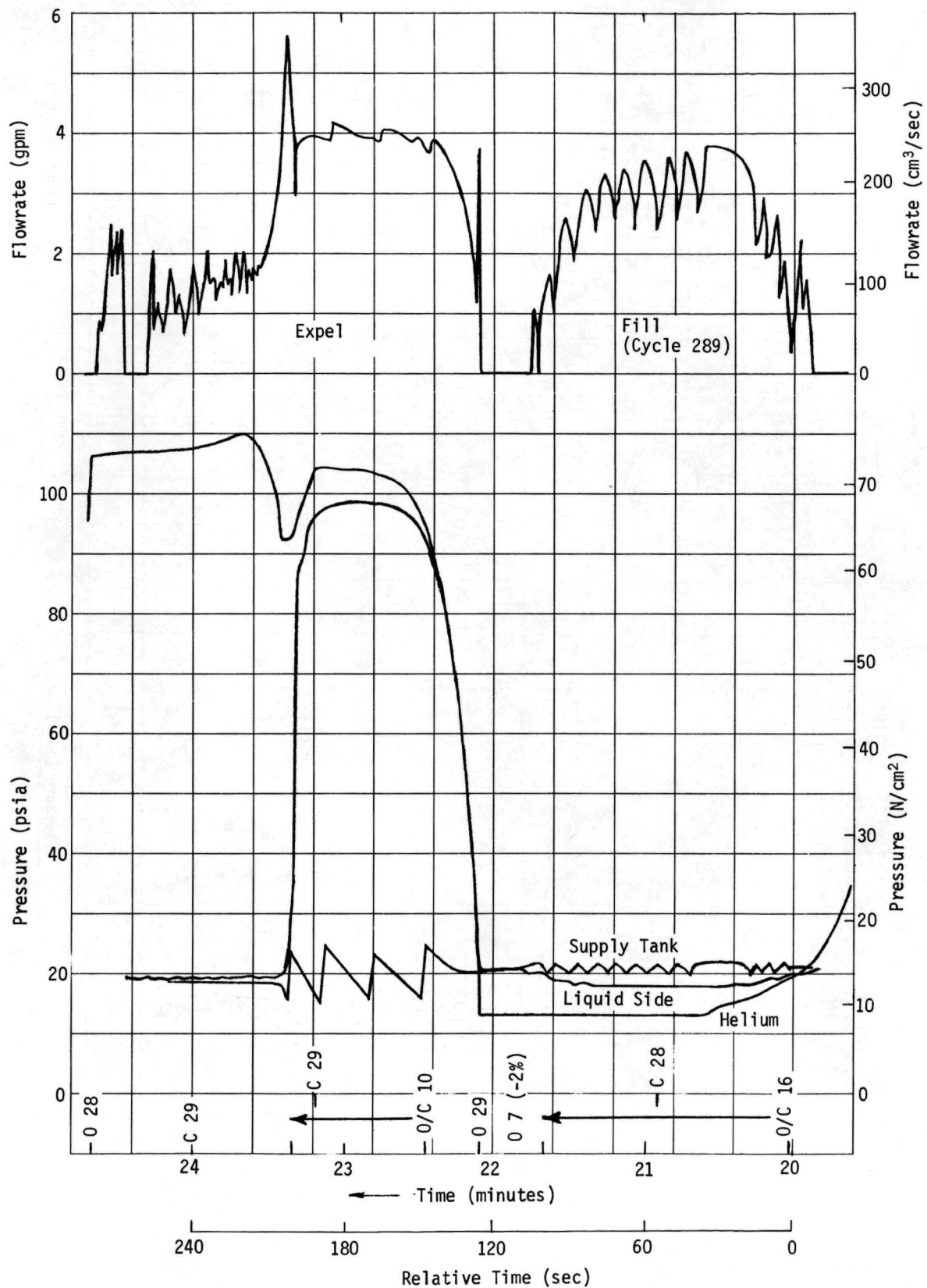


Figure 53 Data for LN₂ Cycle 279 (11/13/70)

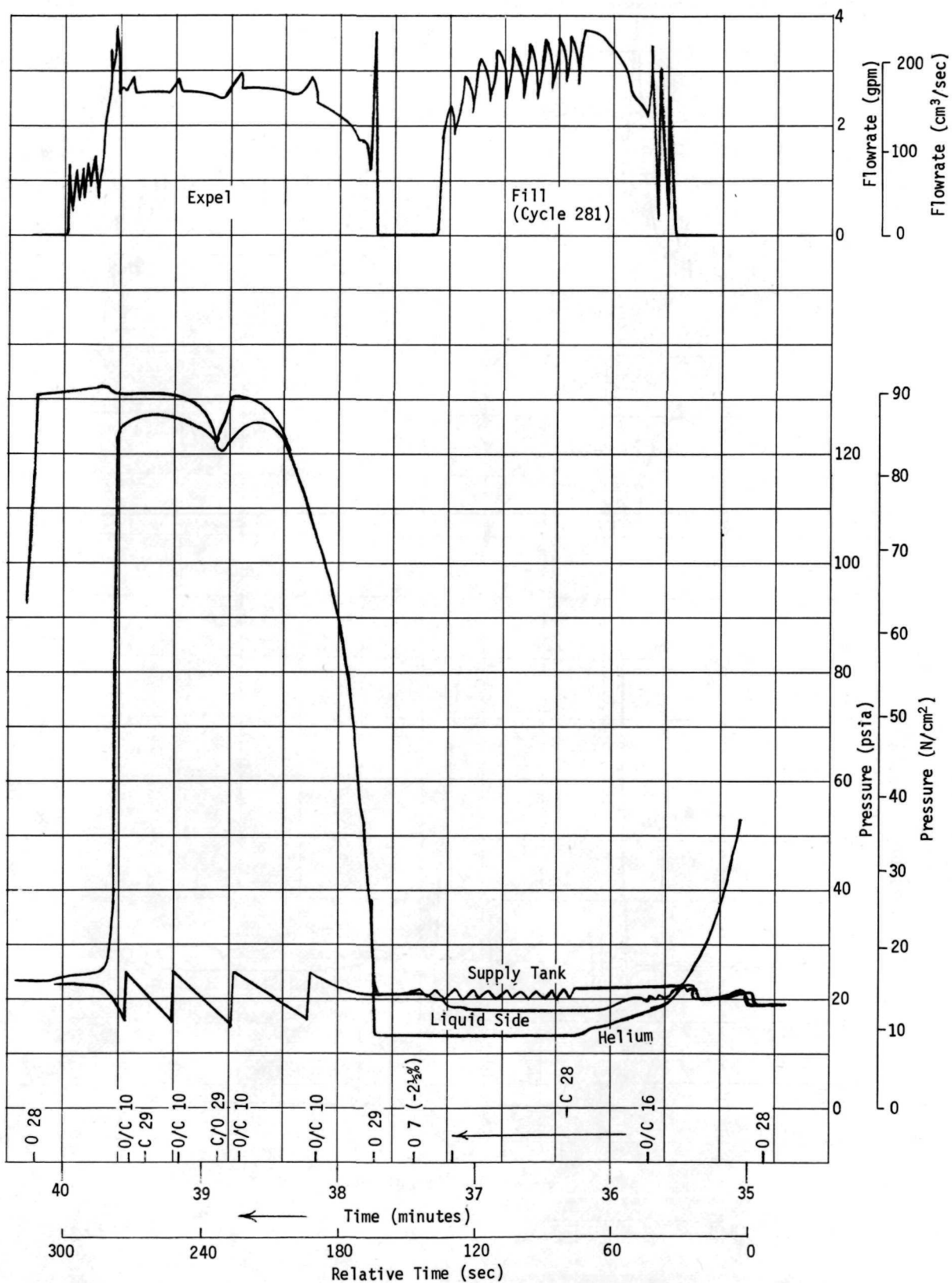


Figure 54 Data for LN₂ Cycle 281 (11/13/70)

Valves 30 and 28 were actuated to purge GN₂ into the liquid side of the bellows until the bellows was fully extended. Then the liquid-side pressure was vented down to 15 psia (10.3 N/cm²) by actuation of valve 11, and evacuation through the roughing pump of the CEC leak detector was continued for several minutes. The purge cycle was completed by pressurizing the gas side of the bellows with GN₂ through valve 32 while pulsing vent valve 11 until the bellows was fully compressed.

Normally a second purge cycle would have been conducted, but this was considered to be superfluous in this case. The bellows already leaked. Therefore, the system was secured, concluding the LN₂ cycle tests of bellows assembly 5.

VII. LF₂ CYCLE TESTS

The objective of the LF₂ cycle tests was to demonstrate the ability of the bellows assembly to perform satisfactorily in liquid fluorine. Suitable test procedures, including those associated with the *in situ* leak of the assembly, had already been thoroughly developed during the LN₂ cycle tests.

Two bellows assemblies were committed to the LF₂ tests; both were to be cycle tested until 100 cycles were completed, or until failure occurred (leak rate $> 10^{-6}$ scc He/sec). Also, the same cycle/leak-check sequence was to be followed for both; i.e., leak checks were to be conducted after cycles 5, 15, 30, 50, 75, and 100. The plan was to conduct all the cycles with the first assembly at relatively low expulsion pressure, ~25 psig (17.2 N/cm², g), then for the second assembly, increase the expulsion pressure in 25 psig (17.2 N/cm², g) increments for each series of tests until the design working pressure of 150 psig (103 N/cm², g) was reached. Because of a defective weld joint in bellows assembly 8, this unit was selected for the first tests (at low expulsion pressure). Assembly 6, thought to be the better of the two, was reserved for the high pressure expulsion cycles.

The test program was conducted exactly as planned, but both bellows assemblies failed prematurely. Both performed satisfactorily through the first three series of cycles (30 cycles total), but developed large leaks (fatigue cracks) at the end of 50 cycles. Detailed discussion of the test program is presented in the following paragraphs.

A. LF₂ CYCLE TEST PREPARATIONS

1. System Cleaning

It was planned to initiate the LF₂ cycle tests immediately after the LN₂ cycle tests were completed. All cycle test system components that might be exposed to fluorine had been cleaned before they were assembled into the system, and it had been expected that the system could be kept free of contaminants following assembly. As it turned out, however, nearly 18 months had elapsed since the parts were cleaned because of the many delays in fabricating a bellows assembly suitable for cycle testing. During this time reasonable precautions had been taken to assure that the system remained clean, but it was not practical to maintain the extremely close surveillance required to guarantee absolute cleanliness. In one instance, for example, it was necessary to break into the system to use the fluorine storage dewar and a portion of the transfer system in another fluorine test program. On completion of the LN₂ cycle tests there was no specific evidence that the system was contaminated; conversely there was no definite proof that it had not become contaminated.

Because of the uncertainty of system cleanliness and the catastrophic results that might be expected if the system actually were contaminated, the decision was made early in December 1970 to reclean the system before use with fluorine. The only technique considered satisfactory for cleaning is at the parts levels. Thus recleaning necessitated complete dismantling of the system, and complete disassembly of components to the parts level. The detailed cleaning procedures are described in Martin Marietta Specification CFL6200154, a specification developed from the previous work accomplished at LeRC and by Douglas Aircraft Company.

Dismantling of the system was begun early in January 1971. Specific components that were recleaned are:

- 1) The fluorine supply tank;
- 2) The four sections of LN_2 -jacketed transfer line;
- 3) Six Annin valves (two were fitted with new seats, two were fitted with reworked seats, all six were leak checked);
- 4) Eight Hoke solenoid valves;
- 5) All of the stainless steel tubing and short spool pieces, tees, crosses, and other interconnecting fittings;
- 6) Instrumentation including two pressure transducers, two Bourdon pressure gages, the Potter flowmeter, and the magnetic float gage used in the fluorine supply tank;
- 7) The Voi-shan gaskets used to seal the flared tubing joints.

No difficulties were experienced during the cleaning operations, except that several Hoke valves leaked slightly. Repairs were attempted, but since the seats are not replaceable in this model valve, the results were not satisfactory. It was necessary to purchase one new valve, in addition to a spare, to have a sufficient number of leak-tight valves for the entire system.

The cycle test system reassembly also proceeded smoothly and was essentially complete by the end of February 1971. The major portion of the system was reassembled in exactly its original configuration (fig. 55). However, new copper lines (used principally between the LF_2 storage dewar and the cycle system supply tank) were installed rather than cleaning the original ones. Also, the lines between the supply tank and the bellows were not reinsulated. It was concluded that the insulation probably is not necessary for the fluorine cycle tests, though it was important for the LN_2 cycle tests. Vapor formation in the lines does not present as large a problem for fluorine as for LN_2 because of the lower vapor pressure of the fluorine.

2. System Checkout

The cycle test system was checked out early in March 1971. Functional checks were made of all the valves to assure that each valve was operative from its respective switch on the control panel. No discrepancies were observed.

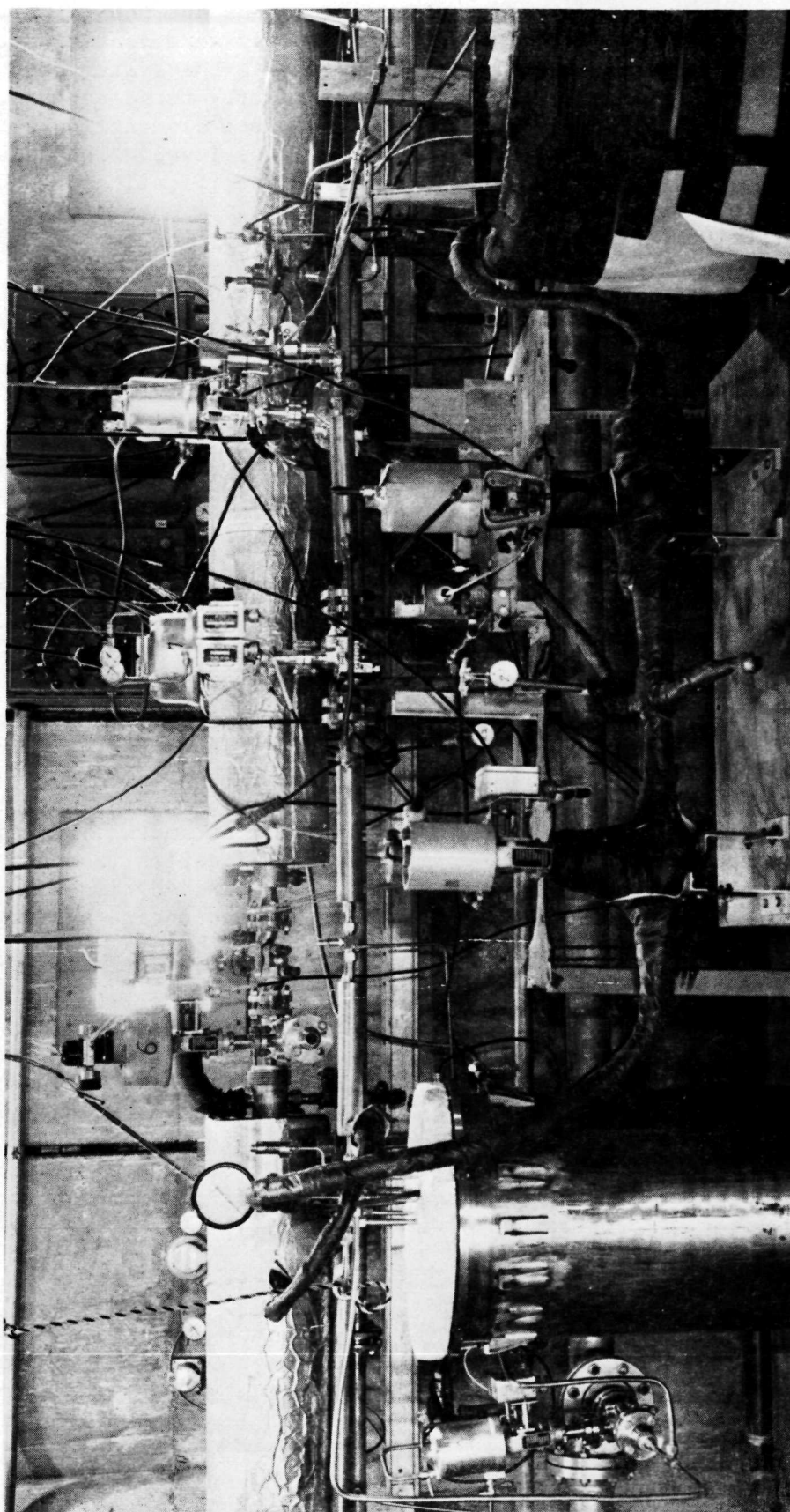


Figure 55 Cycle Test Apparatus after Reassembly

Next, a test was made of the electrical failure mode of the valves by turning off the power to the control panel. Failure of electrical power results in the majority of the valves returning to the closed position, but the following will remain open:

Valve No.

8	LF ₂ dewar vent valve
9	LF ₂ dewar transfer line vent valve
10	Supply tank vent valve
11	Liquid side of bellows vent valve
18	Cyrostat LN ₂ supply valve
19	Insulated tank LN ₂ supply valve

Finally, all system instrumentation was checked out. The three pressure transducers were recalibrated, new thermocouples were installed on the bellows assembly, and the supply tank level sensors (float switches) were reinstalled and checked out. No difficulties of any kind were experienced.

The entire cycle test system was leak checked by pressurizing the system with helium, then bubble checking each joint. This was accomplished in accordance with a formal procedure (Procedure 5.0, included in the Appendix of this report). First the dewar pressurization/vent lines were checked by pressurizing to 100 psig (69 N/cm², g) through valve 13. Then this portion of the system was vented, and the remainder of the system tested. The system was found to be satisfactory, except for minor leaks that were easily eliminated.

3. System Purge and Passivation

Purging and passivation of the cycle test system was conducted late in March using previously prepared formal Procedures 6.0, 7.0, 8.0, and 9.0 (see Appendix). Briefly, the sequence consisted of first purging the system thoroughly with helium to remove any possible remaining contaminant gases, then passivating the system with fluorine in a series of steps.

The system was purged in three major steps:

- 1) The dewar pressurization/vent line was purged for a short period of time through valves 13 and 8;
- 2) The transfer system between the dewar and fluorine supply tank was purged through valves 4, 15, and 10;
- 3) The cycle test system was purged by flowing helium through valves 16, 7 and 11.

No difficulties were encountered during any of the purge sequences.

Passivation was accomplished in a somewhat similar manner, starting with the dewar/supply tank transfer system, and continuing through the cycle test system (including bellows). Initially, it had been planned to passivate from fluorine K-bottles, but after the entire system had been thoroughly recleaned, it was concluded that passivation could be accomplished with adequate safety directly from the dewar. The latter offers a somewhat simpler procedure, though it is more difficult to control. Basically, it involves introducing a very small amount of LF_2 into the portion of the system to be passivated, the liquid immediately flashing to vapor to provide the desired helium/fluorine gas mixture at elevated pressure.

Passivation was accomplished in several steps, starting with a dilute mixture of fluorine and helium at relatively low pressure, and continuing to exposure of the system to essentially pure gaseous fluorine at relatively high, 90 psig (62 N/cm^2 , g) pressure. Specific pressure levels (and corresponding exposure times) were as follows:

15 psig (10.3 N/cm^2 , g), dilute GF_2/He mixture,	5 minutes (300 sec)
15 psig (10.3 N/cm^2 , g), moderate GF_2/He mixture,	10 minutes (600 sec)
25 psig (17.2 N/cm^2 , g), 100% GF_2 ,	25 minutes (1500 sec)
90 psig (60 N/cm^2 , g), 100% GF_2 ,	90 minutes (5400 sec)

Throughout the entire procedure the instrumentation was carefully monitored for any evidence of a reaction or other anomalies, but no discrepancies were observed. Upon completion of the passivation sequences, the system was secured by venting the pressure down to 5 to 10 psig (3.4 to 6.9 N/cm^2 , g), closing the dewar hand valves, and finally purging the line between the dewar and valve 4 with helium.

4. Fluorine Transfer to Supply Tank

The final step in the preparations for fluorine cycle testing was to fill the fluorine supply tank from the dewar. This transfer operation was first initiated on 25 March 1971 in accordance with Procedure 10.0, but the transfer was not completed because of a fluorine leak (thought to be a burnthrough at the time). Consequently, it was necessary to take emergency action to eliminate the fluorine from the system and return it to a safe condition. A summary of these activities follows.

Transfer was initiated by pressurizing the dewar to 20 psig (13.8 N/cm^2 , g), supply tank to 2 psig (1.4 N/cm^2 , g), and then opening valve 4 in the transfer line. By the time the supply tank had become approximately 25% full the two pressures had approximately equalized, so valve 4 was closed while the system was observed for evidence of abnormalities.

After 10 minutes (600 sec) with no discrepancies observed, the dewar pressure was raised to approximately 45 psig (31 N/cm^2 , g), and valve 4 was again opened to resume transfer. Almost immediately crackling noises were heard from the test area, presumably the result of escaping fluorine reacting with portions of the test equipment. Immediately, valve 4 was closed to stop the transfer, and valves 8 and 9 were opened to vent the dewar pressurization and liquid lines to the vent stack.

Test personnel were sent to the test area to observe the dewar from a safe distance of 50 ft (15 m). It was observed that some of the paint on the top of the dewar had been burned, and that the outlet line expansion bellows was blackened. Therefore, it was concluded that a burnthrough had occurred some place in the outlet line, but it could not be determined whether the burnthrough was external to the dewar vacuum jacket.

All nonessential personnel were immediately evacuated from the area, while emergency procedures were initiated to dump all the fluorine from the system, including the dewar. Since there apparently was a leak in the dewar outlet line, it was decided to empty the dewar by purging helium in through the outlet line (through valve 15) and out through the pressurization/vent line (valve 8). This purge operation continued for approximately 5 hr until a flame was observed emanating from the vent stack burner indicating that fluorine was no longer present.

After the dewar had been emptied, procedures were initiated to dump the fluorine from the cycle system supply tank, a quantity estimated to be approximately 7 gallons (0.0265 m^3). This was accomplished by purging helium through the supply tank (through valves 15 and 4) and into the vent stack through valve 10. This required an additional 2 hr to complete.

Further securing of the system included warm up of both the fluorine supply tank and the dewar. A GN_2 purge line was inserted in the cryostat to boil off the LN_2 ; another line was connected to the dewar LN_2 jacket vent line to purge the LN_2 from the jacket.

The following morning the dewar was carefully inspected for evidence of damage. The lower convolutions of outflow line expansion bellows were discolored as a result of burned paint, but there was no evidence of actual damage (fig. 56). Finally, the outflow valve was dismantled by removing the four bolts that hold the body and bonnet of the valve together. It was evident that one of the copper gaskets that seals the replaceable seat in the valve had been leaking slightly. The gasket was not actually damaged, but the surface was discolored in the vicinity of the leak. It was concluded that the tie bolts had loosened slightly as a result of temperature cycling, finally permitting the gasket to leak when the dewar was pressurized to a higher pressure level. The small amount of fluorine that leaked past the gasket then dripped down the line and onto the top of the dewar, reacting with the paint to produce considerable smoke and the crackling noises that had been heard. The system failure was of such a minor nature that no damage was done to any of the test hardware.

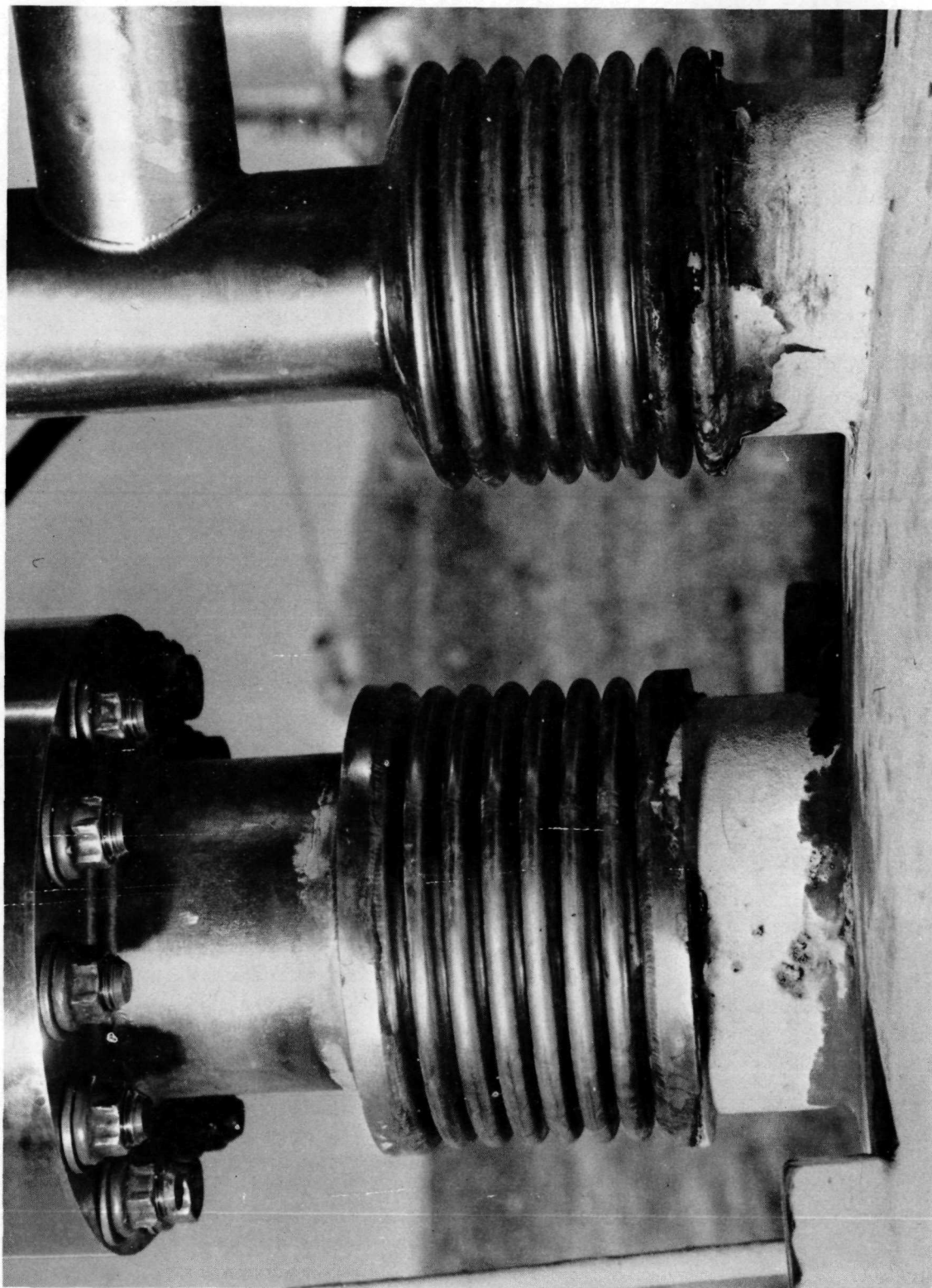


Figure 56 Expansion Bellows on Fluorine Dewar

Following the aborted fluorine transfer operation, the dewar outlet valve was repaired by the installation of new gaskets, and the dewar was thoroughly checked for evidence of other damage. There was no indication that the dewar vacuum jacket had been affected by the aborted transfer operation, but it had reached a higher pressure level than desired, and did need to be reevacuated. Following these repair operations, the dewar was repassivated, reloaded with fluorine from the 5000-lb (2260 kg) mobile dewar, and reconnected to the cycle test system in preparation for loading the system supply tank.

The second attempt to transfer fluorine from the dewar to the supply tank was accomplished without any major difficulties. The same procedure was employed as before. The dewar was pressurized to 25 psig (17.2 N/cm^2 , g), the supply tank vented to 2 psig (1.4 N/cm^2 , g), and transfer initiated by opening valve 4. After the pressures equalized, valve 4 was closed while the dewar was repressurized, and then the transfer continued by reopening valve 4. For some reason, not yet fully explained, the level sensing system in the supply tank did not function properly, and as a result the tank was overfilled. This created no unusual hazards, but it was necessary to back-transfer a portion of the fluorine before securing the system for the day. The supply tank was secured approximately 80% full of fluorine.

B. LF_2 CYCLE TESTS, BELLOWS ASSEMBLY 8

1. LF_2 Cycles 1 thru 5, 4/7/71

During the early morning there was some question whether the weather would be suitable for fluorine cycle testing, but at 9:15 AM approval was given by the Safety Department to proceed. Remaining pretest operations that were performed included:

- 1) An operational check of valve 7 because it had been necessary to readjust the packing. The valve performed satisfactorily;
- 2) The vent stack propane burner was checked out and ignited;
- 3) A final check of the entire test area was made by safety personnel;
- 4) System regulators were set at the desired values for the first series of cycle tests. Settings were as follows:

Valve No.	Setting	
	(psig)	(N/cm ² , g)
1	50	34.5
2	10	6.9
3	50	34.5
12	25	17.2
33	25	17.2
34	50	34.5
23	100	69

- 5) The fluorine supply tank LN₂ bath was topped off, and the bath surrounding the bellows assembly was filled.

The cycle test sequence was then initiated in accordance with Procedure 11.0. The final sequences performed before initiating the bellows fill for the first cycle were to vent the bellows liquid-side pressure down to 2 psig (1.4 N/cm², g) through valve 11 to eliminate as much of the helium as possible, and then to open valve 7 to 15% to equalize the pressure in the two portions of the system. Bellows fill was then initiated by venting the bellows gas-side pressure through valve 28. A reasonably constant fill rate was maintained by pressurizing the fluorine supply tank through valve 16. The valve was cycled open and closed to maintain a pressure of 18 to 22 psia (13 to 15 N/cm²). Cycling was employed to preclude the possibility of backflowing fluorine gas through the pressure regulator (valve 2). As was the case for the LN₂ cycle tests, the system pressures and flowrate oscillated somewhat due to the presence of residual helium, but this was expected. Filling required 3 3/4 minutes (225 sec) to complete.

Expulsion was initiated by opening valve 29 to pressurize the gas side of the bellows. The expulsion flowrate was maintained essentially constant by repeated venting of the supply tank pressure through valve 10. Supply tank pressure was maintained in the range of 15 to 20 psia (10 to 14 N/cm²), which again precludes backflow of gas through valve 2 even though valve 16 might have a slight leak. Expulsion was uneventful, requiring approximately 2 minutes (120 sec) to complete.

After a short pause to assure that all system conditions were normal, the second cycle was successfully conducted in exactly the same manner as the first, then the third cycle was conducted. By this time the majority of the residual helium had been purged from the system as evidenced by only minimal oscillations of the turbine flowmeter readout.

The final two cycles were completed following exactly the same sequence as for the previous cycles. The fifth expulsion was completed approximately 30 minutes (1800 sec) after the first fill had been initiated. Personnel then entered the cell to check for any indication of abnormal conditions or fluorine odor, but no discrepancies were observed. Pertinent valve events and the system

pressures and flowrates during a typical cycle (the fifth one) are presented in figure 57.

Warm up of the bellows assembly in preparation for the leak check was initiated by opening the LN₂ bath drain valve 26 (see Procedure 12.0). Five minutes later the upper heater on the bellows assembly was turned on at 80 volts; 20 minutes (1200 sec) later it was turned down to 50 volts. Then the lower heater was turned on to 60 volts. After a total elapsed time of 1 hr, the LN₂ bath was fully drained and the drain valve was closed.

Shortly after noon vent-down of the liquid-side pressure was initiated. By this time, the thermocouples on the bellows assembly indicated a slight rise in temperature, and the gas-side and liquid-side pressures had risen from 35 to 41 and 22 to 37 psia (24 to 28 and 15 to 25 N/cm²), respectively. As was the case for LN₂ cycle tests conducted some months ago, it was necessary to cycle the vent valve many times before the pressure finally remained at a low value. The first few vents expel the majority of the liquid from the system, but a large number of vents is required to fully evaporate all of the liquid from the system. Until this is accomplished, the pressure attempts to stabilize each time at the vapor pressure corresponding to the mean temperature of the bellows assembly. In this particular case, valve 11 was cycled ~130 times before the pressure finally stabilized at a slightly positive (gage) value.

The first steps in the purge sequence were to enter the test cell to set valve 34 to a lower setting, 10 psig (6.9 N/cm², g) for the purge operation, and to connect the vacuum pump into the system for evacuation of the gas side of the bellows. Following this, helium was purged into the liquid side of the bellows by alternate cycling of pressurization valve 30 and vent valve 28 until the bellows was moved from the fully compressed to the fully extended position. Then the vacuum pump was started, and the helium pumped out of the gas side of the bellows through valve 25 for several minutes. Next GN₂ was purged into the gas side of the bellows through valve 32 while valve 11 was cycled several times to vent the liquid-side pressure and permit the bellows to return to the fully compressed condition. The first purge cycle proceeded somewhat slowly; then a second purge cycle was conducted and the system was secured for the day.

The bellows leak check was conducted the following morning in accordance with Procedure 13.0. After valves 11 and 28 had been cycled to vent system pressures to nearly ambient, the heat exchanger was disconnected from the bellows inlet, and the vacuum hose to the leak detector connected in its place. Then the bellows was pumped down through the leak detector vacuum pump in preparation for a leak rate measurement. In the meantime, a calibration of the leak detector was conducted. The system pumped down rapidly, and within an hour it was possible to obtain a satisfactory reading. Leak rate was $<10^{-7}$ scc He/sec, so the test was terminated. Then the vacuum was broken by purging GN₂ into the gas side of the bellows through valve 35, and the heat exchanger was reconnected to the bellows assembly in place of the vacuum line. The leak check sequence was concluded by repressurizing the bellows (gas side) to 33 psia (22.7 N/cm²) through valve 29 while cycling valve 11 as required until the bellows was fully seated in the compressed condition.

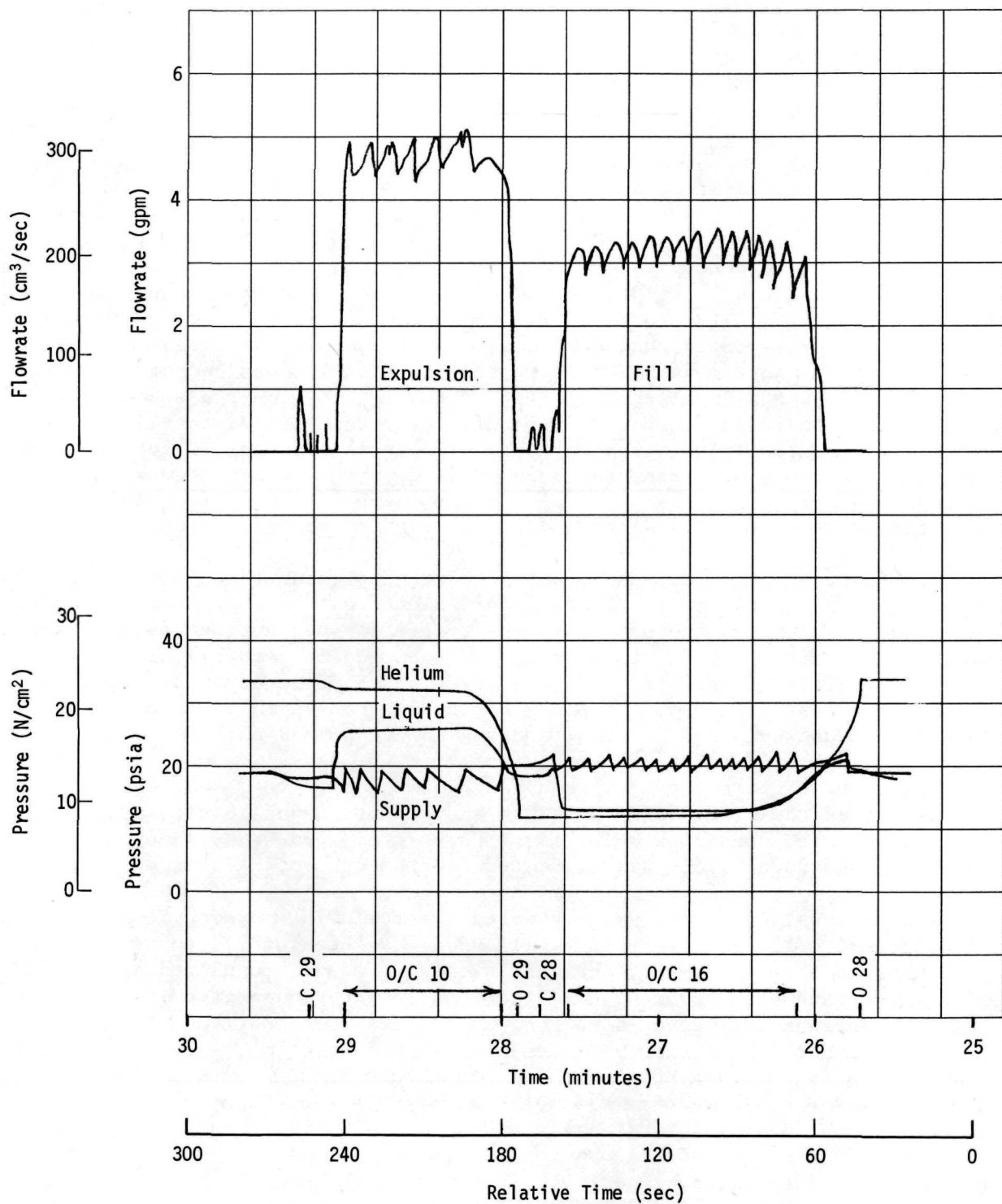


Figure 57 Data for LF_2 Cycle 5 (4/7/71)

2. LF₂ Cycles 6 thru 15, 4/8/71

When the leak check of the bellows was completed, preparations were begun for the second series of LF₂ cycles, to consist of 10 complete cycles. The only significant operations that had to be performed were the resetting of the regulators, and the refilling of the LN₂ bath surrounding the bellows. Only two regulators required resetting, valves 12 and 34. Valve 12 was reset to 25 psig (17.2 N/cm², g) to accomplish expulsion in exactly the same manner as previously; valve 34 was reset to 50 psig (34.5 N/cm², g) simply to preclude backflow of fluorine through valve 30 during cycle test sequence.

The 10 cycles were conducted in exactly the same manner as before, except that throttling valve 7 was opened to 20% this time (instead of 15%) to effect an increase in flowrate. The first cycle was begun at 9:40 AM, the last (tenth) expulsion cycle was completed 40 minutes (2400 sec) later. All cycles employed identical valve operational sequences, resulting in repeatable cycle characteristics except for the effects of residual helium on the first few cycles. Recorded fluorine flowrates for the first cycle are reproduced in figure 58. Similar characteristics were obtained for the next two cycles, but the last seven cycles were almost identical to data shown in figure 57 (the fifth cycle conducted the previous day). Following the last cycle, personnel again entered the test cell to check for evidence of abnormal conditions or an odor of fluorine. No discrepancies were observed.

The warmup sequence proceeded exactly as before. After approximately 45 minutes (2700 sec), venting of the liquid-side pressure was initiated. Approximately 30 vent cycles (valve 11) were conducted during the next few minutes, dropping the liquid-side pressure from 39 to 20 psia (27 to 13.8 N/cm²). Subsequently, 40 to 50 additional cycles of valve 11 were accomplished, lowering the pressure to ~16 psia (11 N/cm²). The gas- and liquid-side pressures during this vent-down sequence are reproduced in figure 59.

The purge sequence was conducted in the same manner as the previous day, following the same basic procedure. Significant events are shown graphically in figure 59. The system was then secured for the day in accordance with Procedure 14.0. The most important step in this procedure is to refill the supply tank LN₂ bath to assure that pressure will not build up in the supply tank overnight as a result of fluorine boiloff.

The leak check of the bellows was conducted early the following morning, employing the standard procedure as before. The pumpdown of the system proceeded much more slowly than it did for the previous leak check, because of helium outgassing from the vacuum hose. Therefore, it was decided to procure additional vacuum hose so that new hose could be installed, only 3 ft (0.9 m), are required for each leak check to be conducted. An exact leak rate was not measured (equilibrium conditions were not attained), but the leak rate was determined to be $<10^{-6}$ scc He/sec.

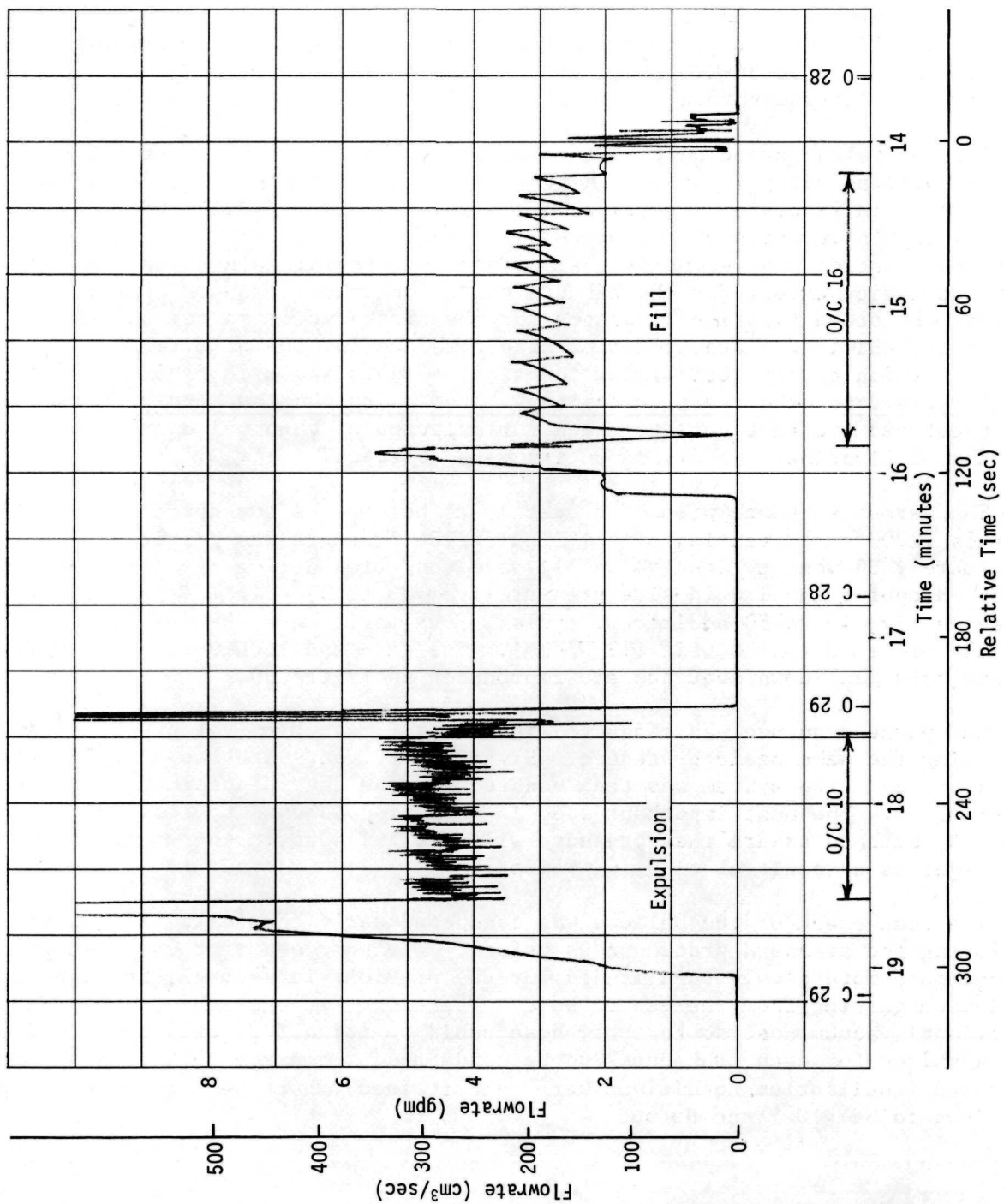


Figure 58 Data for LF₂ Cycle 6 (4/8/71)

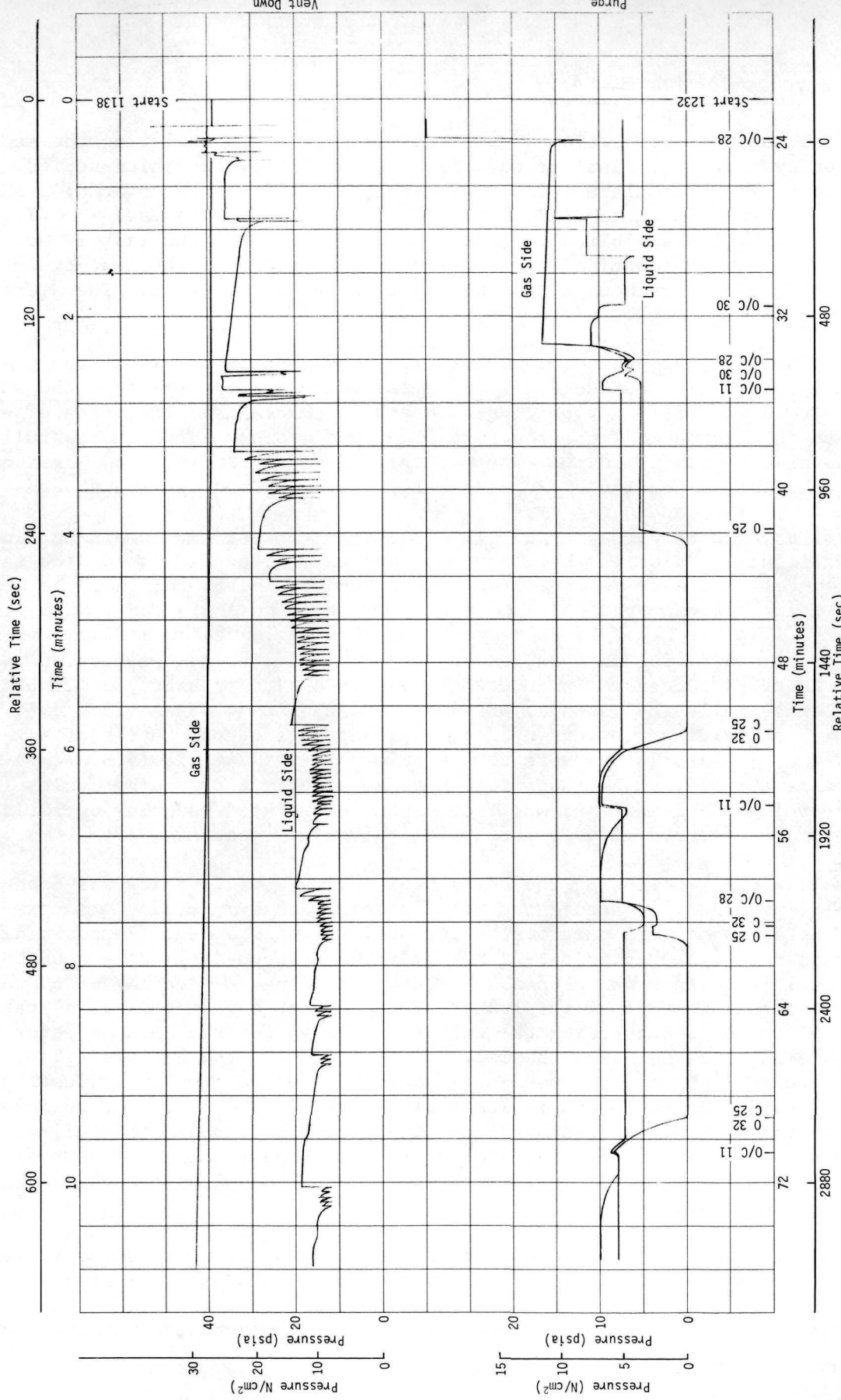


Figure 59 Warmup and Purge History (4/8/71)

3. LF₂ Cycles 16 thru 30, 4/9/71

Upon successful completion of the bellows leak check following the second series of cycle tests, final preparations were made for the third series, this one to comprise 15 complete cycles. The initial fill was begun at 8:45 AM. The cycle sequence proceeded as in the previous series of tests. The first two or three cycles exhibited the usual oscillations, but the last 12 were very "clean," and almost identical to that shown in figure 57. The last cycle was completed less than an hour after the start of the first cycle. The average cycle required $\sim 3\frac{1}{2}$ minutes (210 sec) to complete.

At this point the sequence of operations was changed somewhat from that previously used. It was decided to back-transfer the fluorine from the supply tank to the dewar before proceeding with other operations. The transfer was conducted in accordance with Procedure 15.0, and was completed successfully by midmorning. Then the cycle test system (Procedure 12.0) and the transfer system (the latter portion of Procedure 15.0) were warmed up simultaneously.

After an hour of warmup, valve 11 was cycled to vent the remaining fluorine from the liquid side of the bellows. At this time both the liquid-side and gas-side pressures were reading 42 psia (29 N/cm²), indicating that the bellows was no longer fully compressed. No net pressure decrease in the liquid system was observed in the first 15 vent cycles, indicating that the bellows was simply being compressed during this series of vent cycles. The next series of 20 vent cycles, however, succeeded in reducing the liquid-side pressure to ~ 20 psia (13.8 N/cm²), while the gas-side pressure remained at ~ 42 psia (29 N/cm²). Subsequently, a series of 10 vent cycles, followed by a second series of six cycles, reduced the liquid-side pressure to a stable value of 14 psia (9.6 N/cm²). Since there appeared to be insufficient time to conduct the purge cycles (required for leak checking) and still complete the weekend securing operations, the system was secured without performing the purge sequence.

The leak check following the third series of LF₂ cycle tests was conducted the following Monday in accordance with Procedure 12.0. Purging was completed shortly before noon, and pumpdown of the bellows was started. Pumpdown did not proceed as rapidly as anticipated, but by 1:20 PM the system was evacuated sufficiently to obtain an acceptable leakrate reading. A reading of 60 was obtained on the 50-scale of the leak detector, which corresponds to a leakrate of $\sim 9 (10)^{-7}$ scc He/sec, using the calibration data for the leak detector. Since this leakrate is below the maximum specified for the bellows (i.e., 10^{-6} scc He/sec) the bellows was judged suitable for further cycle testing. It is believed that the measured leakrate was simply the result of residual helium in the system, and was not the actual leakrate through the bellows. A true leakrate could have been determined by continued pumping of the system for a number of hours, but these data were not considered valuable enough for the time and effort involved.

Immediately following the leak check, preparations were begun to refill the fluorine supply tank in anticipation of conducting an additional series of cycle tests the next day. The last operation as part of the leak-check procedure was to disconnect the vacuum hose from the bellows assembly and reconnect

the heat exchanger so that bellows pressurization was again controlled by valves 28 and 29. Then the transfer operation was conducted in accordance with Procedure 10.0. Transfer was completed in midafternoon with the supply tank 80% full, and the dewar was secured.

4. LF₂ Cycles 31 thru 50, 4/13/71

This series of tests was conducted in the same manner as the previous series, except that a total of 20 cycles was run, and test personnel entered the cell after each group of five cycles to inspect for any evidence of fluorine leakage. Because of adverse weather conditions (both wind direction and humidity were unsatisfactory), testing was delayed until after noon.

The first few cycles were characterized by several excursions of the flowmeter as residual helium was being expelled from the liquid system, but this was typical. No evidence of fluorine leakage was detected following the fifth cycle.

The second set of five cycles was completed in 16 minutes (960 sec). Again the test area was inspected, but no discrepancies were observed. The third and fourth sets of five cycles each were conducted in a similar manner, the last cycle (the 50th cycle conducted on this bellows) being completed by midafternoon. The cycles required slightly less than four minutes (240 sec) each, including the time involved in inspecting the test area.

All the cycles appeared to be normal, except that a flow perturbation was noted approximately halfway through some of the expulsion cycles. This perturbation occurred on both the flowrate and the liquid-side pressure recorders. The recorded data for these two measurements on cycle 41 are reproduced in figure 60. The other two measurements (supply tank and bellows gas-side pressures) did not indicate this same perturbation. No explanation has been found for this anomaly, but it does not appear to have any particular bearing on the overall performance of the bellows. At first it was thought that this might be related to the development of a leak in the bellows, but careful review of some of the previous cycle test data disclosed that this same perturbation was present in some of the earlier cycles. For example, the 9th, 10th, 11th, 12th, and 13th cycles conducted the previous day exhibited this same characteristic, but the other cycles did not.

Warmup of the system for the leak check began as soon as the final test area inspection was completed. By 3:30 PM the system had warmed sufficiently to initiate the venting of the residual fluorine from the bellows. The gas-side and liquid-side pressures had equalized at 61 psia (42 N/cm²), indicating that the bellows was no longer fully compressed, but was only partially extended.

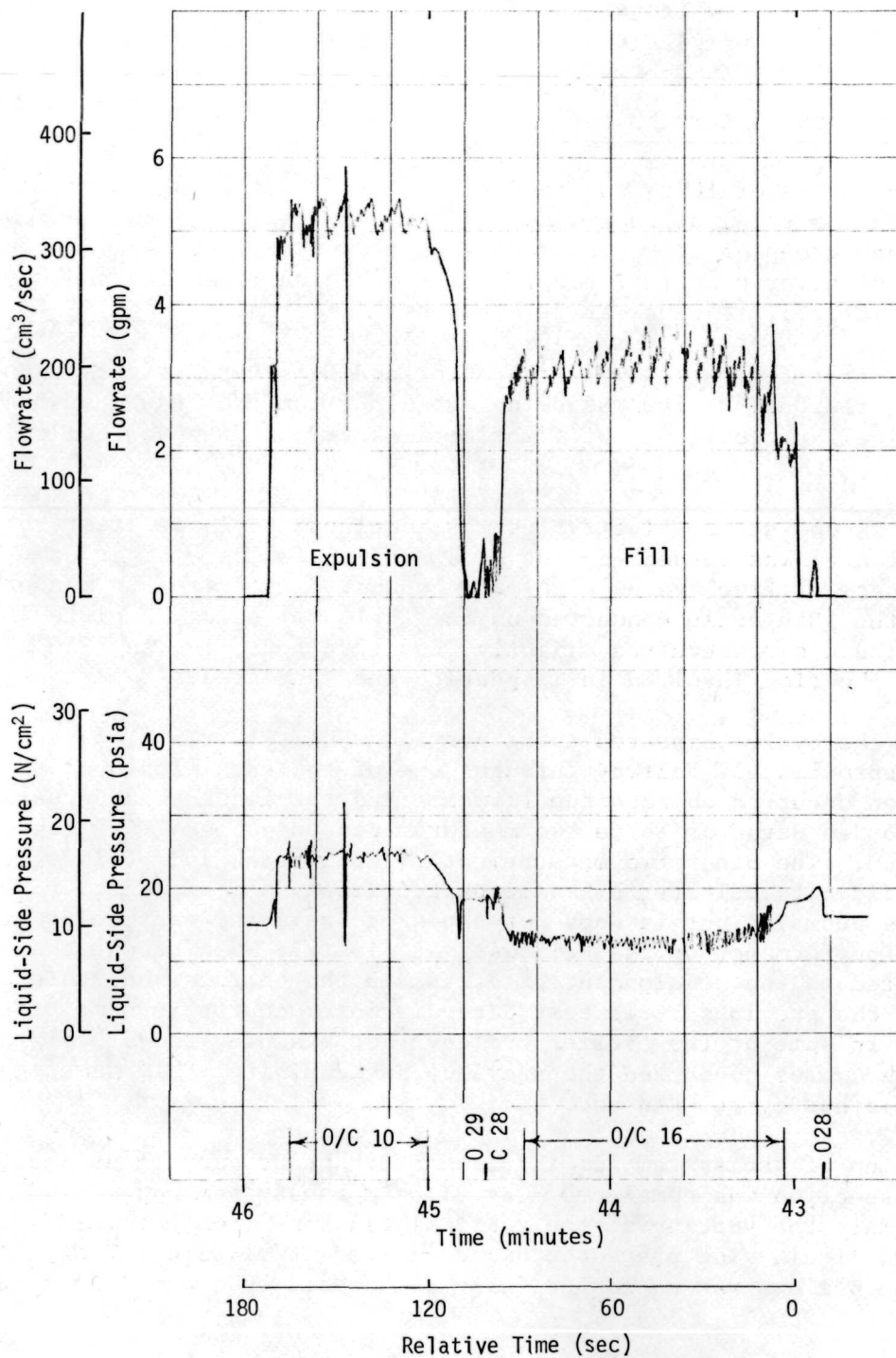


Figure 60 Perturbation during LF_2 Cycle 41 (4/13/71)

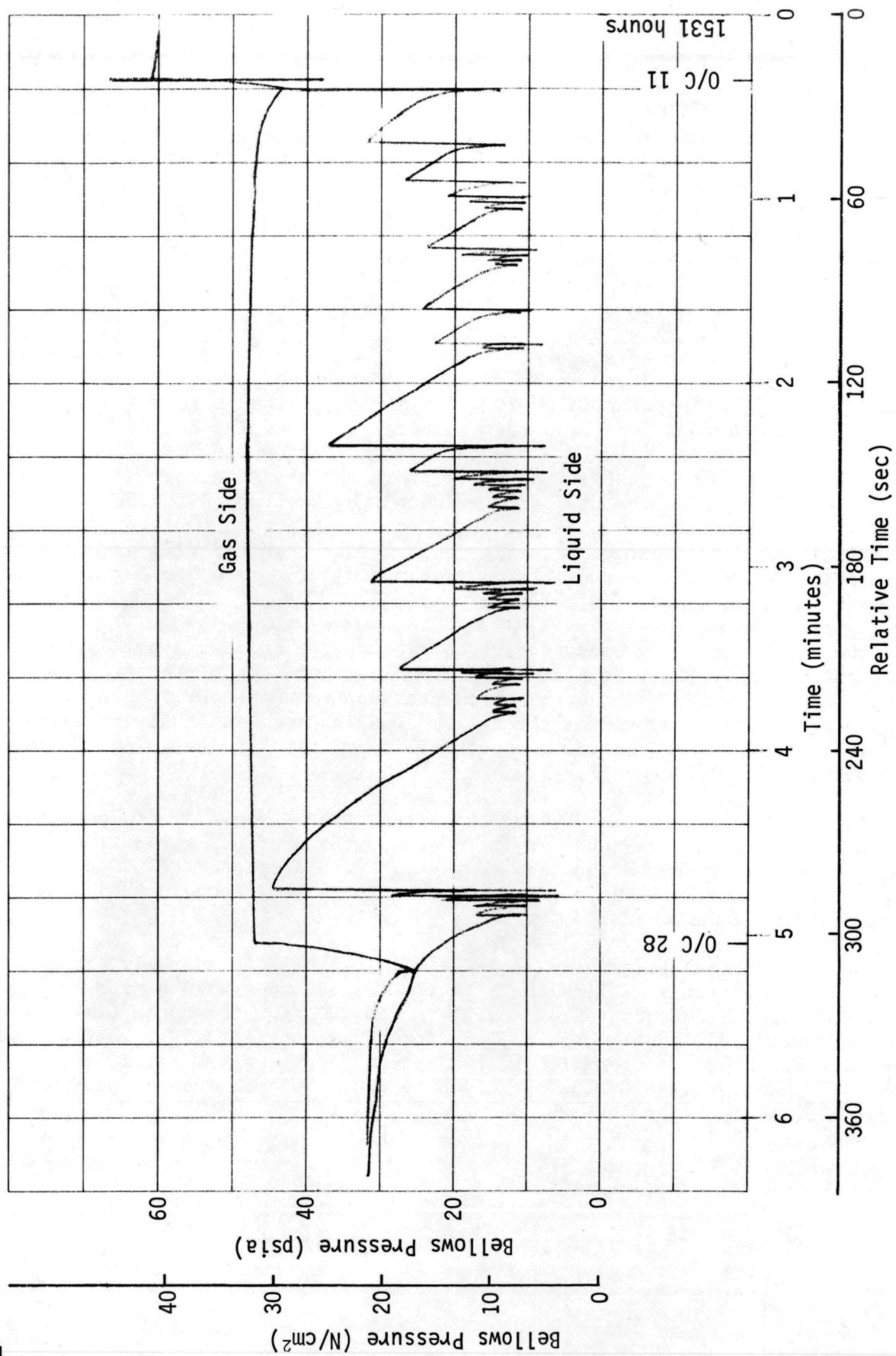
The initial cycle of valve 11 seated the bellows, thereby dropping the gas-side pressure to ~47 psia (32 N/cm^2). Continued cycling of valve 11 dropped the pressure to approximately ambient, but each time it rose fairly rapidly to again approach the gas-side pressure. Approximately 40 vent cycles were conducted during a 5-minute (300 sec) period without producing any permanent reduction in pressure. Pressure history during this time interval is reproduced in figure 61. Note that the rate of pressure rise following each vent is ~40 psi/minute ($0.46 \text{ N/cm}^2\text{-sec}$) until the liquid-side pressure approaches the gas-side pressure. This pressure history is significantly different from the normal pressure history during vent down (e.g., fig. 59), and is a definite indication of a leak through the bellows.

For the next several hours a number of tests were conducted to determine whether the bellows had developed a leak. Another possible explanation for the repeated rise in pressure on the liquid-side of the bellows is a helium leak through valve 30, which is used to purge the fluorine from the bellows before the leak check. Such a leak would increase the liquid-side pressure until it balanced the gas-side pressure, then the pressure would stay essentially constant while the bellows moved from the compressed to the fully extended condition. This would of course, produce a pressure history almost identical to that actually measured. Such a leak combined with a very slight leak from the bellows pressurization system could even produce a gradual decay in both the liquid-side and gas-side pressures.

The tests that were conducted revealed that the bellows liquid-side pressure always approached the gas-side pressure, regardless of the relative values of the latter and the regulated pressure to valve 30. Therefore, it was definitely concluded that the bellows was leaking, and that the system had to be secured to preclude the possibility of fluorine entering the bellows pressurization system.

At 7 PM the system was secured by entering the test cell, disconnecting the pressurization line, and capping off both the pressurization line and the bellows inlet. Then the liquid-side pressure was increased to ~40 psia (27.6 N/cm^2) to preclude leakage of fluorine through valve 7 into the bellows, and test operations were secured for the night.

Because of the excessively large leak in the bellows assembly, there was no point in attempting a leak check in the usual manner with a mass-spectrometer leak detector. Instead, the assembly was removed from the cycle test system and subjected to a bubble check. Before removal, the liquid side of the bellows was thoroughly purged with helium by cycling valves 30 and 11 for 40 cycles. Then the liquid line was disconnected, the open ends capped, and the bellows assembly taken into the shop for examination.

Figure 61 Vent-Down Sequence Following LF₂ Cycle 50 (4/13/71)

After removing the flange bolts, the bellows was removed from the pressure vessel and carefully inspected for evidence of distortion or damage. None was evident. Then the bellows was pressurized slightly with GN_2 , and the bubble check conducted. Two leaks were discovered in the longitudinal weld joints. One leak was in the crest of the 20th convolution from the open (guide-ring) end of the bellows; the other was located 180 deg (3.14 radians) from the first one (in the other weld joint) in the crest of the 18th convolution. No immediate attempt was made to determine the size of the leaks, but they were obviously orders of magnitude greater than the 10^{-6} scc He/sec leak rate considered acceptable. It is possible that other very small leaks were also present, but these were not discernible. Therefore, this concluded cycle testing of bellows assembly 8. Further evaluation of the leaks in the bellows is discussed in a following chapter.

C. LF_2 CYCLE TESTS, BELLOWS ASSEMBLY 6

Since the LF_2 cycle test apparatus and the bellows had performed as expected, except for the relatively short cycle life of the bellows assembly 8, there appeared to be no reason for changing the plan for testing the second assembly (6) in LF_2 . The same basic schedule of cycles and leak checks was followed for assembly 6 as for assembly 8, but higher expulsion pressures were included. The first series of five cycles would be conducted exactly as for assembly 8, then the expulsion pressure would be raised in increments of ~ 25 psi (17.2 N/cm²) for each succeeding series until the maximum working pressure of 150 psig (103 N/cm², g) is reached.

Before initiating the cycle tests of assembly 6, several minor modifications were incorporated in the test hardware:

- 1) Valve 12 (a low-pressure regulator) was replaced with a Victor regulator capable of operating at regulated pressures up to 200 psig (138 N/cm², g);
- 2) The low-pressure relief valve was removed from the facility helium line;
- 3) The two 100 psig (69 N/cm², g) gages measuring the bellows gas-side and liquid-side pressures were replaced. A 400 psig (276 N/cm², g) "clean" gage was installed on the liquid-side of the bellows; a 300 psig (207 N/cm², g) gage in the bellows pressurization line.

Concurrently, the bellows assembly was readied for test. It was carefully cleaned (on the exterior), and the pressure vessel interior was cleaned before assembling them into a single unit. A new flange gasket was installed, and the flange bolts again torqued to 200 in.-lb (13.8 N-m).

On 14 April 1971 the bellows assembly was installed in the cycle test system, and the system leak checked by pressurizing it to 150 psig (103 N/cm^2 , g) through the recently installed pressure regulator (valve 12). All joints were bubble checked, and several nuts were retorqued to eliminate small leaks.

The following day the system was passivated. In general, Procedure 9.0 was followed, but some of the steps were omitted because all of the system except the bellows had been passivated previously. The bellows was passivated in two steps:

- 1) Gaseous fluorine from the supply tank was introduced into the bellows through valve 7 to a pressure of 4 psig (2.8 N/cm^2 , g) and held for 5 minutes (300 sec) while the bellows was in the compressed condition;
- 2) The bellows was moved to the fully extended position and exposed to fluorine gas at a pressure of 12 psig (8.3 N/cm^2 , g) for 30 minutes (1800 sec).

The system was then secured for the day in accordance with the standard procedure.

1. LF_2 Cycles 1 thru 5, 4/16/71

Final preparations for the cycle tests were begun at 7:30 AM. The usual precycle tasks were performed, including:

- 1) Set up of the regulators;
- 2) Filling the LN_2 baths for the fluorine supply tank and the bellows;
- 3) Cooldown of the fluorine transfer line through valve 21.

These tasks were completed in approximately an hour, and transfer of the fluorine from the dewar to the supply tank was completed shortly thereafter.

The first bellows fill cycle was initiated shortly thereafter, after first venting down the liquid-side pressure to 2 psig (1.4 N/cm^2 , g) and opening valve 7 to 20%. The first five cycles were conducted in exactly the same manner as previous cycles, and were completed in 35 minutes (2100 sec) without incident. As usual, the first three cycles showed evidence of residual gas (helium) in the system; the last two cycles were much improved. The recorded flowrates were almost identical to the typical ones shown in figures 57 and 58.

At this point it was decided to back-transfer the fluorine from the supply tank into the dewar (a normal weekend securing operation) before proceeding with the system warmup. The transfer was accomplished without incident, employing Procedure 15.0.

Warmup of the system was allowed to proceed for nearly $1\frac{1}{2}$ hr, then vent-down of the liquid-side of the bellows was initiated. At this time both the liquid- and gas-side pressures were 69 psia (48 N/cm^2) indicating that the

bellows was partially, but not fully, extended. The first cycle of valve 11 resulted in both pressures dropping to ~50 psig (35 N/cm², g), indicating that the bellows was still partially extended. Three more rapid cycles of valve 11 dropped the liquid-side pressure to ~35 psia (24 N/cm²), while the gas-side pressure stabilized at nearly 50 psia (35 N/cm²), indicating that the bellows was now seated in the compressed condition. Twenty additional cycles of valve 11 conducted during the next few minutes were sufficient to complete the vent-down sequence with the liquid-side pressure stabilized at ~17 psia (12 N/cm²). Finally valve 28 was opened to vent the gas-side pressure to 36 psia (25 N/cm²), followed by valve 11 which vented the liquid-side pressure to 14 psia (9.6 N/cm²).

Before continuing with the bellows purge sequence, additional weekend securing operations were performed. First a GN₂ purge line was inserted in the LN₂ bath surrounding the fluorine supply tank to accelerate the boiloff of the LN₂. Then as the supply tank warmed up and the residual fluorine was vaporized, valve 10 was cycled until the supply tank pressure stabilized at ~20 psia (14 N/cm²).

Shortly after noon the purge sequence was begun. It proceeded in the usual manner in accordance with the latter portion of Procedure 12.0. The first evacuation of the bellows with the vacuum pump was continued for 10 minutes (600 sec). Then GN₂ was purged into the bellows, followed by the second evacuation of 10 minutes (600 sec). On completion of the purge sequence, the gas-side and liquid-side pressures were stabilized at 20 and 16 psia (14 and 11 N/cm²), respectively. Then the remaining weekend securing operations (Procedure 15.0) were completed.

The following Monday the leak-check sequences were conducted in accordance with Procedure 13.0, but considerable difficulty was experienced in pumping the assembly down to an acceptable pressure level. It is believed that the slow pumpdown was the result of continued outgassing of the new vacuum hose, or it is possible that the bellows purge was not as effective as usual. It was decided to allow the system to set overnight under vacuum. The following morning the bellows assembly pumped down very rapidly. It was quickly established that the leak rate was acceptable ($<10^{-6}$ scc He/sec), and that cycle testing could proceed.

2. LF₂ Cycles 6 thru 15, 4/27/71

After one week of inactivity because of unfavorable weather conditions, the second series of fluorine cycle tests of bellows assembly 6 was conducted on 27 April 1971. Pretest operations including setting of regulators, filling the LN₂ baths, and cooldown of the LF₂ transfer line were completed by 9:45 AM. Regulator 12 was set at 25 psig (17 N/cm², g) to provide the same expulsion pressure that has been used for the previous cycles.

Fluorine was transferred from the storage dewar to the cycle system supply tank without incident in accordance with Procedure 10.0. Then the first bellows fill cycle was initiated after first venting down the liquid-side pressure to 2 psig (1.4 N/cm^2 , g) and opening valve 7 to 15%. Four cycles were conducted in exactly the same manner as previous cycles, and were completed by midmorning. As usual, the first two or three cycles showed evidence of residual gas (helium) in the system; the fourth cycle was much improved. The recorded flowrates were almost identical to the typical ones shown in figures 57 and 58.

Following the fourth cycle, test personnel entered the test cell to inspect for evidence of any fluorine leaks and to reset regulators 12 and 34 to 50 psig (34.5 N/cm^2 , g) in preparation for expulsion at higher pressures. No fluorine odor was detected, so the second set of six cycles was initiated at 10:34 AM. The bellows was filled exactly as before, but before expulsion valve 7 was reset from 15% to 2% to provide greater throttling in an attempt to maintain the expulsion flow rate at $\sim 5 \text{ gpm}$ ($315 \text{ cm}^3/\text{sec}$). This valve setting had proved satisfactory during the LN_2 cycle tests at this expulsion pressure, and also proved satisfactory for the LF_2 cycles.

Upon completion of the expulsion portion of the cycle, valve 7 was reset to 15% open, and the next fill cycle initiated. By 11:00 AM a total of six cycles had been completed at this higher expulsion pressure, pausing each half-cycle to reset valve 7 to the proper opening. Recorded data from a typical cycle (cycle 11) is presented in figure 62. Note that the expulsion flowrate is more steady than in previous tests, presumably the result of the liquid being subcooled to a greater degree.

Warmup of the system proceeded as in previous tests in accordance with Procedure 12.0. By noon the gas-side and liquid-side pressures had reached 57 and 51 psia (39 and 35 N/cm^2), respectively, and vent-down was initiated. Forty-three vents were accomplished in a 12-minute (720 sec) period, then 18 additional vent cycles succeeded in reducing the two pressures to 23 and 14 psia (16 and 10 N/cm^2), respectively.

The system was purged in the usual manner without incident, employing the latter portion of Procedure 12.0. The second purge cycle was completed early in the afternoon and evacuation of the bellows was initiated. By 4:20 PM it was possible to obtain a leak-rate measurement, but the pumpdown was proceeding slowly. Therefore, it was decided to secure for the day and complete the leak check the following day. The system was secured with the gas side of the bellows under vacuum, and the liquid-side pressure slightly above ambient.

The following morning the leak-check sequence was resumed. The system pumped down rapidly and it was quickly established that the leak rate, if any, was less than $10^{-6} \text{ scc He/sec}$, and the bellows was suitable for further cycling. The final operations of the leak-check sequence were to break the bellows vacuum with a helium purge and reconnect the heat exchanger before resuming cycle testing.

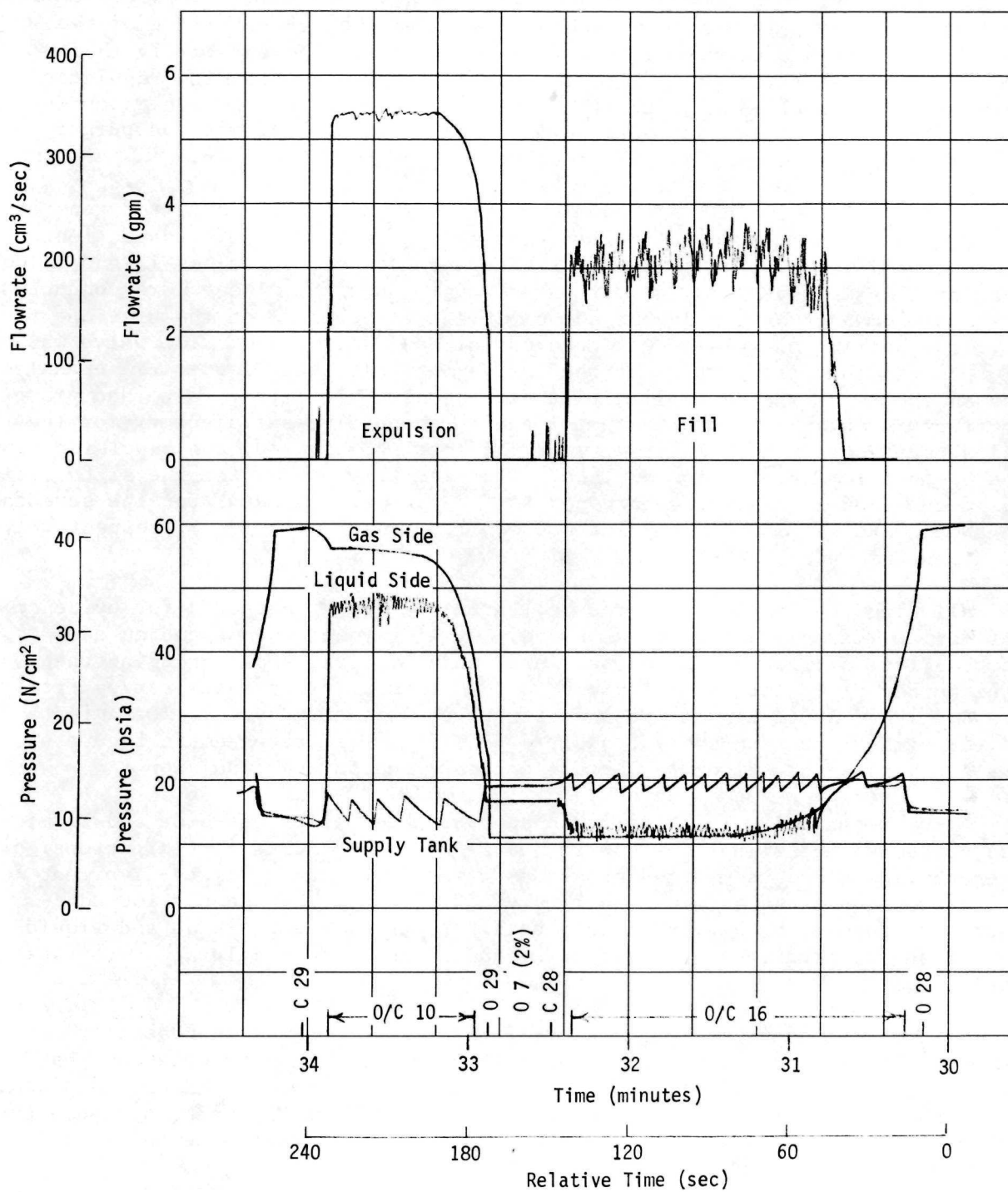


Figure 62 Data for LF_2 Cycle 11 (4/27/71)

3. LF₂ Cycles 16 thru 30, 4/28/71

The third series of cycle tests of bellows assembly 6 was conducted on 28 April 1971 immediately following the bellows leak check. Refilling of the bellows LN₂ bath was completed by 9:00 AM, and cycling began shortly thereafter. The first five cycles were conducted at low pressure with regulator 12 set at 25 psig (17 N/cm², g), the same as for the first few cycles conducted the previous day. This procedure permits the residual helium to be purged from the system without danger of overspeeding the turbine flowmeter.

The first five cycles were completed in 20 minutes (1200 sec) and generated data equivalent to that previously cited in figures 57 and 58. Inspection of the test cell revealed no evidence of fluorine leakage, so valves 12 and 34 were reset to 80 psig (55 N/cm², g) for the remaining cycles. These were conducted in the same manner as the second set of five cycles conducted the previous day; i.e., the setting of valve 7 was changed for each half-cycle. The valve was set 15% open for the fill portion of the cycle, then was throttled to ~1% open (as read on the Swarthout controller) for expulsion. This latter value had proved satisfactory for the LN₂ cycle tests, and was generally satisfactory for the LF₂ cycles. Because of the sensitivity of the setting, however, the expulsion flowrate was not completely reproducible. The peak flowrate during the sixth cycle was ~6 gpm (380 cm³/sec) then dropped to 4.7 gpm (296 cm³/sec) for the seventh and eighth cycles, and was 4.2 and 4.6 gpm (270 and 290 cm³/sec), respectively for ninth and tenth cycles.

Following the tenth cycle, the cell area was again inspected for evidence of fluorine leakage, but none was noted. Cycling then resumed and an additional five cycles were conducted in 22 minutes (1320 sec), bringing the total number of cycles on assembly 6 to 30. Expulsion flowrates ranged from 4 to 4.7 gpm (260 to 295 cm³/sec) during these last five cycles. Data for a typical cycle (the 13th cycle conducted this date) is presented in figure 63. Note the very stable flowrate measurement obtained during expulsion.

Warmup began at 10:15 AM. Within an hour the bellows gas-side and liquid-side pressures had risen to 100 psia (69 N/cm²), indicating partial extension of the bellows, and the vent-down sequence was initiated. Thirty-five vent cycles were conducted within four minutes (240 sec). Then nearly 100 additional cycles were accomplished in a half hour until the gas-side and liquid-side pressures finally stabilized at 29 and 14 psia (20 and 10 N/cm²), respectively.

The purge sequence was begun shortly after noon and was successfully completed in 25 minutes (1500 sec). The leak check was begun immediately thereafter. By midafternoon a satisfactory leakrate measurement had been obtained; i.e., leakrate <10⁻⁶ scc He/sec. Preparations were quickly made to resume cycle test operations, but weather conditions were no longer favorable for fluorine operations, so it was necessary to secure for the day.

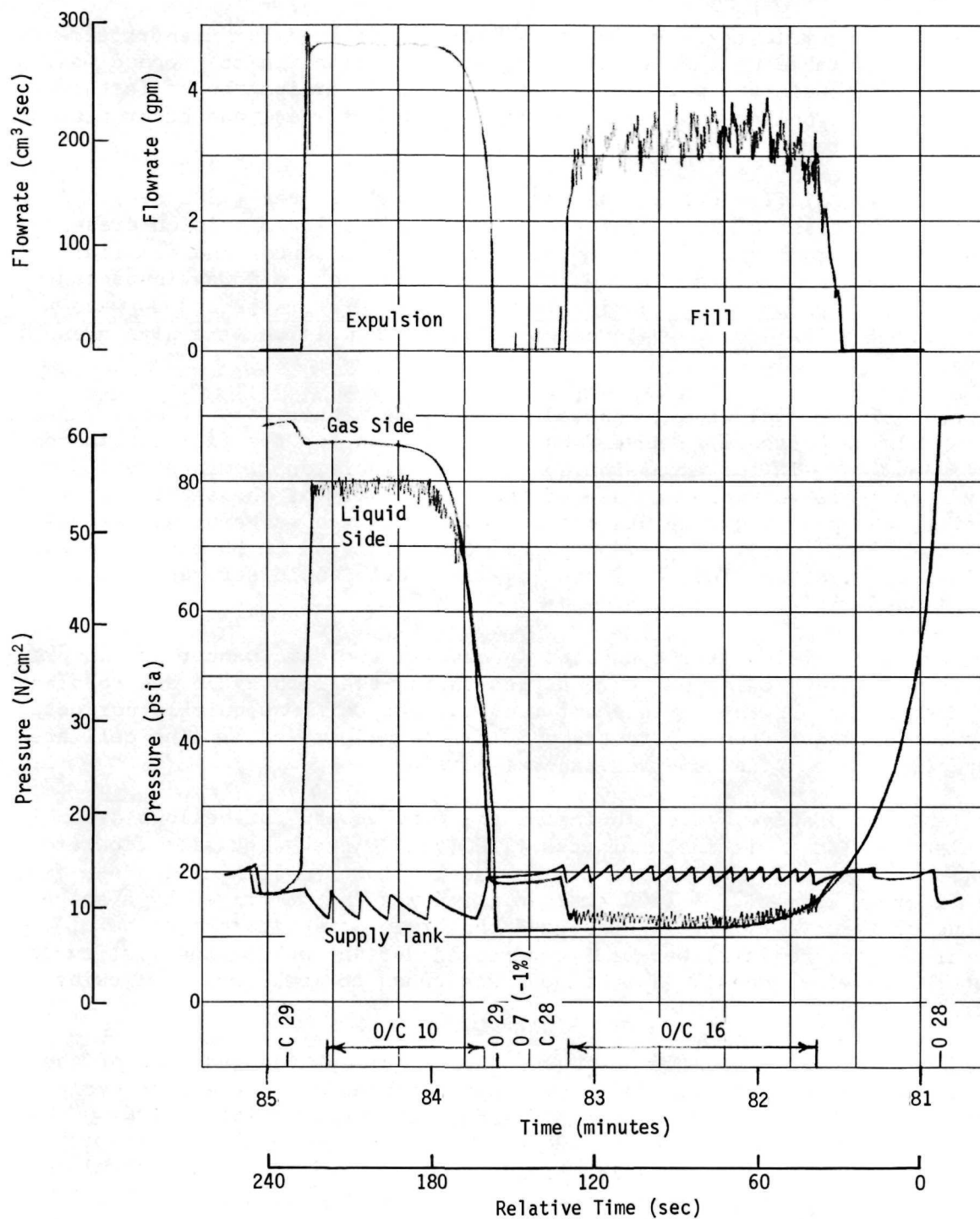


Figure 63 Data for LF_2 Cycle 28 (4/28/71)

4. LF₂ Cycles 31 thru 50, 4/29/71

Initiation of cycle tests on 29 April 1971 was delayed for a short time because of unfavorable weather conditions, but authorization to proceed was obtained from the Safety Department at 9:05 AM. In anticipation of further cycle testing, the bellows LN₂ bath had already been filled, and other pretest operations completed.

The first set of five cycles was completed in 20 minutes (1200 sec). As before, this first set of five cycles was conducted at low expulsion pressure, regulator 12 set at 25 psig (17 N/cm², g), and again produced the familiar cycles previously shown (fig. 57 and 58). Then the test cell was inspected to assure that there were no fluorine leaks, and regulators 12 and 34 were reset to 150 psig (72 N/cm², g) in preparation for expulsion at a high pressure level.

The next five cycles were conducted in the same manner as previous cycles at high expulsion pressure. Valve 7 was set 15% open for the fill portion of the cycle, and at ~1% for expulsion. Again the expulsion flowrate varied slightly from cycle to cycle because of the sensitivity of the setting of valve 7. However, the peak flowrate was maintained within the range of 4.5 to 5.1 gpm (284 to 322 cm³/sec). The five cycles were completed in 20 minutes (1200 sec). Inspection of the test cell area again revealed no discrepancies, so cycling resumed.

The next five cycles were conducted in exactly the same manner as the previous five. A slight delay was encountered during the 11th cycle due to binding of paper in one of the strip chart records, but this was quickly corrected. Peak flowrates ranged from 4.7 to 6.4 gpm (297 to 403 cm³/sec). The cell area was inspected again, with no discrepancies noted.

The last set of five cycles (bringing the total to 50 for bellows assembly 6) was also completed within 20 minutes (1200 sec). Peak expulsion flowrates ranged from 4.7 to 5.4 gpm (297 to 340 cm³/sec). For the 18th cycle (see fig. 64) the flowrate was 5.1 gpm (322 cm³/sec), and was characterized by a spike at the end of the cycle. It is suspected that this spike is indicative of a leak through the bellows, because it occurred during each of the last cycles (but not the previous ones). The bellows was found to leak badly following this series of cycles.

To avoid reaching excessive pressures during warmup, the gas side of the bellows was vented to ~50 psia (32 N/cm²) upon completion of the last cycle. Then valve 7 was closed, and the normal warmup sequence was initiated. Venting of the residual fluorine in the system was delayed because of unfavorable weather conditions, but was finally initiated shortly after noon. By this time the gas-side and liquid-side pressures had risen to 90 psia (50 N/cm²), indicating that the bellows was partially extended. Fifty-two vent cycles were conducted within a few minutes, dropping the gas-side and liquid-side pressures to 32 and 20 psia (20 and 13 N/cm²), respectively. However, the latter pressure continued to climb after each vent cycle, leading to speculation that the bellows was leaking.

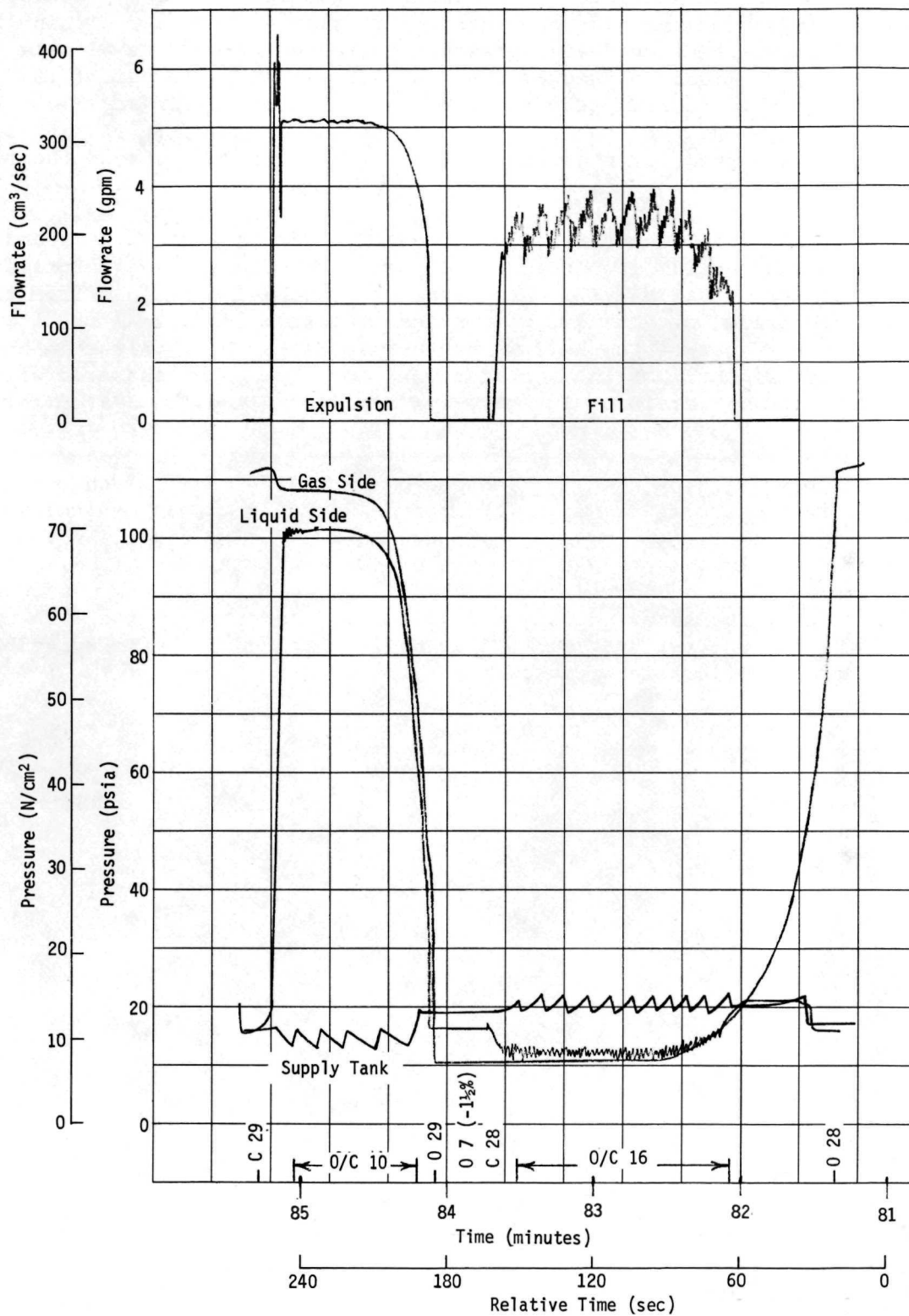


Figure 64 Data for LF_2 Cycle 48 (4/29/71)

During the next 45 minutes (2700 sec) 63 additional vent cycles were conducted. To further investigate the suspected presence of a leak, regulator 12 was reset to raise the gas-side pressure to 78 psia (49 N/cm^2). Within 12 minutes (720 sec), the liquid-side pressure increased from 22 to 41 psia (14 to 26 N/cm^2). The liquid-side pressure was then vented to 12 psia (7.5 N/cm^2), but climbed again to 45 psia (28 N/cm^2) within 15 minutes (900 sec). By this time it was fairly evident that the bellows was leaking, but it was decided to proceed with the normal purge sequence to eliminate the majority of the fluorine from the bellows.

Two complete purge cycles were conducted in accordance with the standard procedure, purging helium into the liquid-side of the bellows and nitrogen into the gas-side. Initially it was planned to remove the bellows from the system at this point, but then it was decided to attempt a normal *in situ* leak check first. Pumpdown of the bellows began in midafternoon. After $1\frac{1}{2}$ hr of pumping it was evident that the leak rate was too high to be measured with the CEC leak detector. Therefore, the test was terminated and the system secured for the day.

The following morning the fluorine was back-transferred from the system supply tank to the storage dewar. Then the bellows (expulsion device) was removed from the cycle test system and taken into the shop for inspection. The bellows assembly was removed from the pressure vessel, installed in the exercise fixture, and subjected to a bubble leak check. One leak was found, located in one of the longitudinal weld joints on the crest of the 18th convolution from the guide-ring. Since this bellows was no longer serviceable, this concluded the fluorine cycle test program.

VIII. POSTCYCLE TESTS AND FAILURE ANALYSIS

A. EXPULSION EFFICIENCY TESTS

Upon completion of the LN₂ cycle tests, and before the beginning of the LF₂ cycle tests, a series of tests was conducted to determine the expulsion efficiency of the bellows assembly. Bellows assembly 5 was used for these tests. This assembly was the one that had been used previously to conduct the LN₂ cycle tests. The fatigue crack that had developed during cycling was temporarily repaired with Devcon cement so that valid volumetric data could be obtained.

The apparatus used for the test is shown schematically in figure 65; a photo is shown in figure 66. Major components include a funnel, a container, two gages (one pressure, one vacuum), several valves, a vacuum pumping system, a K-bottle pressure source, a glass graduate, and interconnecting plumbing.

The first attempt to conduct the test did not produce accurate results, but did identify several changes in system technique and hardware required to accomplish more rapid and accurate testing. Subsequently, the apparatus was modified, and testing resumed. Air leakage into the bellows assembly introduced some error in the first two tests attempted, but this was corrected and the third test produced very accurate data.

The testing technique selected involved the direct measurement of the bellows outage volume (volume remaining on the liquid side of the bellows following expulsion) to provide a high degree of accuracy. The expulsion efficiency of a device of this type is generally defined as:

$$\eta = \frac{\text{Volume Expelled}}{\text{Volume to Fill}}$$

In theory, it is only necessary to measure these two volumes directly to obtain the efficiency, but the errors associated with this approach can be very large. The two volumes are very nearly equal for a device of high efficiency, therefore, small errors in the measurement of either volume may result in a relatively large percentage error in the computed efficiency. The foregoing equation, however, can be rewritten in another form which provides the basis for the test technique actually used; i.e.,

$$\eta = 1 - \frac{\text{Outage Volume}}{\text{Outage Volume} + \text{Displacement}}$$

Since the outage volume is very small relative to the displacement of the bellows, the only measurement that must be made with a high degree of accuracy is the outage volume, and this may be easily done. The basic procedure that was used to conduct the test was:

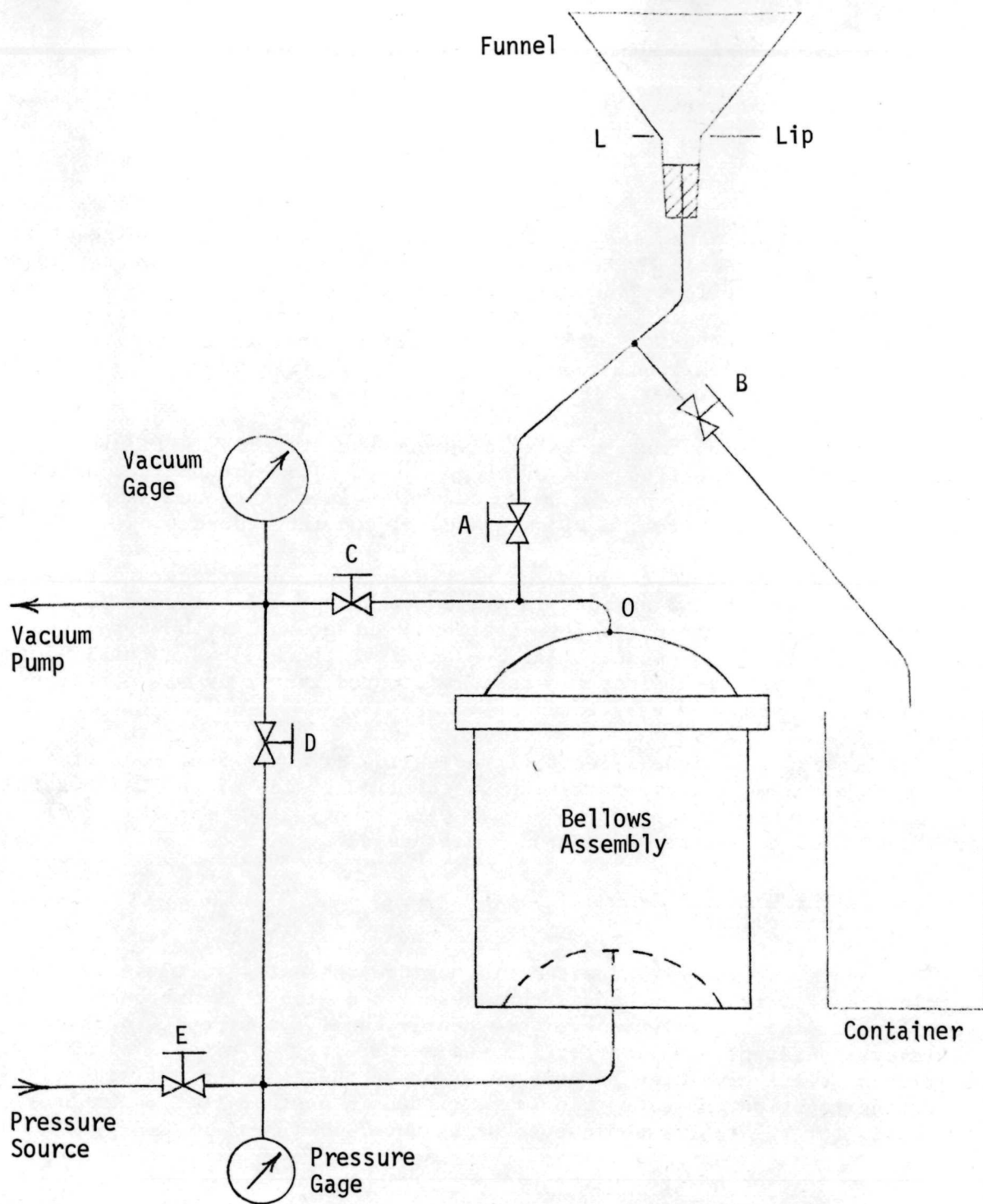


Figure 65 Expulsion Efficiency Apparatus Schematic

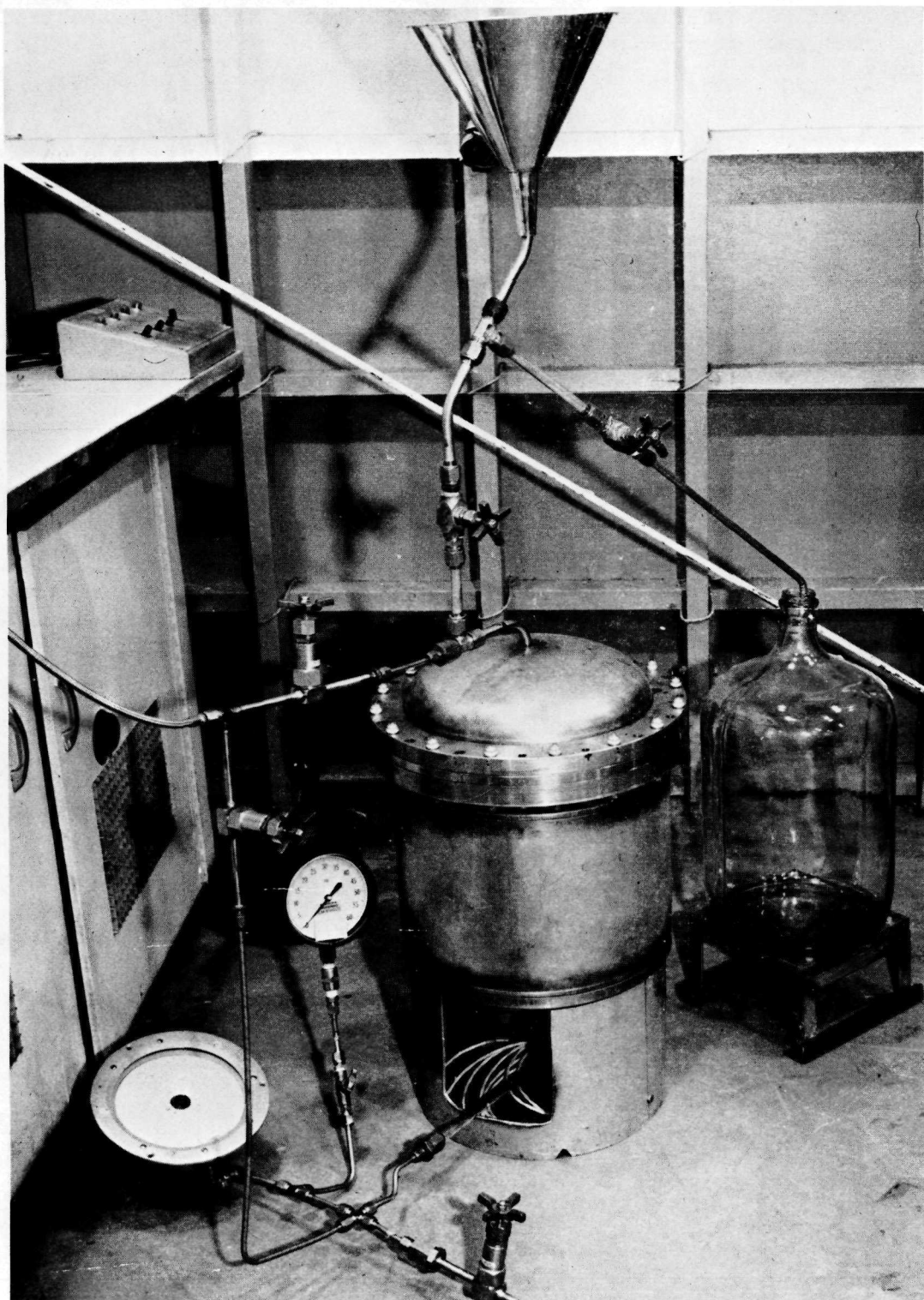


Figure 66 Expulsion Efficiency Test Apparatus

- 1) Determine the outage volume by directly filling the liquid side of the bellows with water (liquid side initially evacuated, gas side of bellows pressurized with GN_2);
- 2) Determine the bellows displacement during extension by venting the gas side and filling the liquid side with water;
- 3) As a check on step 2), determine the bellows displacement by re-pressurizing the bellows and outflowing the water into a calibrated container.

The step-by-step procedure is presented in the following paragraphs.

1. Outage Volume Measurement

The following procedure was used to measure the outage volume:

- 1) With all valves initially closed, valve E (fig. 65) was opened to pressurize the gas side of the bellows to ~ 10 psig (6.9 N/cm^2 , g);
- 2) Valve C was opened to seat the movable dome and evacuate the liquid side of the bellows to nearly zero absolute pressure;
- 3) The funnel was filled with distilled water to the lip (see fig. 65), while being careful to assure that all air was vented from volume ABL. Then an additional 1000 cm^3 of water, accurately measured with a glass graduate, was poured into the funnel;
- 4) Valve C was closed to isolate the vacuum system, then valve A was slowly opened to permit the water to drain into the evacuated bellows assembly;
- 5) After the flow stopped, valve A was closed to isolate the liquid side, and valve B was opened to drain the water back down to the initial level at the lip of the funnel;
- 6) The amount of water drained out was measured with a graduate and found to be 434 cm^3 . Consequently the net amount of water introduced through valve A was 566 cm^3 (this is the outage volume plus volume OAC).

2. Bellows Displacement during Fill

The procedure to determine bellows displacement during fill was as follows:

- 1) The GN_2 pressurization line was disconnected and valve E opened to vent the bellows gas-side pressure down to ambient;
- 2) Water was added to the funnel in 500 cm^3 increments while valve A was manipulated to drain the water from the funnel into the bellows. Care was taken to maintain the water level well above the funnel lip to preclude air being sucked into the system;
- 3) After the bellows was completely full, as evidenced by a stabilized level in the funnel, valve E was closed and valve D opened to evacuate the gas side of the bellows and firmly seat the bellows (movable dome) in the extended position;

- 4) Then valves D and A were closed, and valve B opened to again drain the water down to the lip in the funnel;
- 5) The quantity of water drained out was found to be 205 cm^3 , and the quantity that had been added to the funnel was $37 \times 500 = 18,500 \text{ cm}^3$, hence, the net amount introduced to move the dome through its full travel (the bellows displacement) was $18,215 \text{ cm}^3$.

3. Bellows Displacement during Expulsion

The procedure used to displace the bellows during expulsion was as follows:

- 1) Valve E was opened to bleed the gas-side pressure back to ambient;
- 2) The GN_2 pressurization line was reconnected, and valve E opened to pressurize the gas side to $\sim 3 \text{ psig}$ (2 N/cm^2 , g);
- 3) Valve A was opened slowly to permit expulsion of water from the bellows into the funnel. Only a few small bubbles were seen emerging from the funnel, indicating that the initial evacuation had been complete, and that no air had been sucked into the system during the test;
- 4) Valve B was opened to initiate draining of the water from the funnel into a glass jug, then valves A and B were manipulated to maintain a relatively high outflow rate while maintaining an essentially constant level in the funnel;
- 5) When expulsion was complete, as evidenced by a rapid drop in the funnel water level, valve B was closed;
- 6) Valve E was opened to pressurize the gas side to $\sim 10 \text{ psig}$ (7 N/cm^2 , g) and assure positive seating of the bellows dome, then closed;
- 7) Valve B was opened to again drain the water level back down to the funnel lip, then the valve was closed.
- 8) The volume of water contained in the jug was measured by transferring it into a 500 cm^3 graduate, and found to be $(36 \times 500) + 250 = 18,250 \text{ cm}^3$. This is the volume displaced during expulsion, which compares very favorably with that measured during fill; i.e., $18,215 \text{ cm}^3$;
- 9) The apparatus was secured.

4. Expulsion Efficiency Results

The remaining quantity that must be determined to compute expulsion efficiency is the volume OAC, which must be subtracted from 566 cm^3 to obtain the outage volume. It was concluded that the volume of this portion of the system could not be easily be determined by filling it with water, so the volume was calculated. The section from the seat of valve A to the center of the tee is 1/2-in. (12.7 mm) OD and $\sim 6 \text{ in.}$ (15.2 cm) long; the section from the tee to the seat of valve C consists of a 3/8-in. (9.5 mm) OD tube 4 in. (10.2 cm) long, plus a 1/4-in. (6.3 mm) OD tube 4 in. (10.2 cm) long; and the section

from the center of the tee to the bellows domes is a 1/2-in. (12.7 mm) OD tube 5-1/2 in. (14 cm) in length. Determining the tube inside diameters from the wall thickness, the total volume of this portion of the system was computed to be 35 cm³. Therefore, the outage volume is ~531 cm³. Note that the computed volume OAC is only 6% of the outage volume, consequently it need not be known with a high degree of accuracy.

Using the volumes determined above, the expulsion efficiency may then be computed as follows:

$$\eta = 1 - \frac{531}{18,781} = 1 - 0.028 = 97.2\%$$

Using the value 18,215 instead of 18,250 in the computation would have essentially no effect on the final result.

B. POSTTEST LEAK CHECKS

To size the leaks that had developed in the three bellows that had been cycle tested (one in LN₂, two in LF₂), a quantitative leak check was made on each. To accomplish this, the bellows assembly was installed in the exercise fixture, immersed in water, and pressurized internally with helium. The exercise fixture was necessary to retain the bellows at its normal extended position while applying a positive internal pressure. The bellows was pressurized to ~14 psig (9.6 N/cm², g) with helium, then the bubbles issuing from the cracks in the convolutions were channeled into an inverted glass graduate. Figure 67 shows the stream of small bubbles from one of the cracks flowing upward into the graduate. Timing the volume of displaced water then permitted the leak rate to be calculated. Leak rate data are tabulated below.

Bellows Number	Volume Displaced (cm ³)	Time (sec)	Leak Location (Convolution No.)	Leak Rate (cm ³ /sec)
5	50	554	18	0.09
8	50	60	18, 21, & 23	0.83
	50	26	26 & 27	1.92
6	50	52.4	18	0.95
	3	600	11	0.005

Note that the leak rate for bellows 5 (cycle tested in LN₂) is relatively low, but this may be a false measurement due to partial plugging of the leak. This leak had been temporarily sealed with rubber cement to permit the expulsion efficiency test to be conducted, and subsequent cleaning of the crack may not have been completely effective.

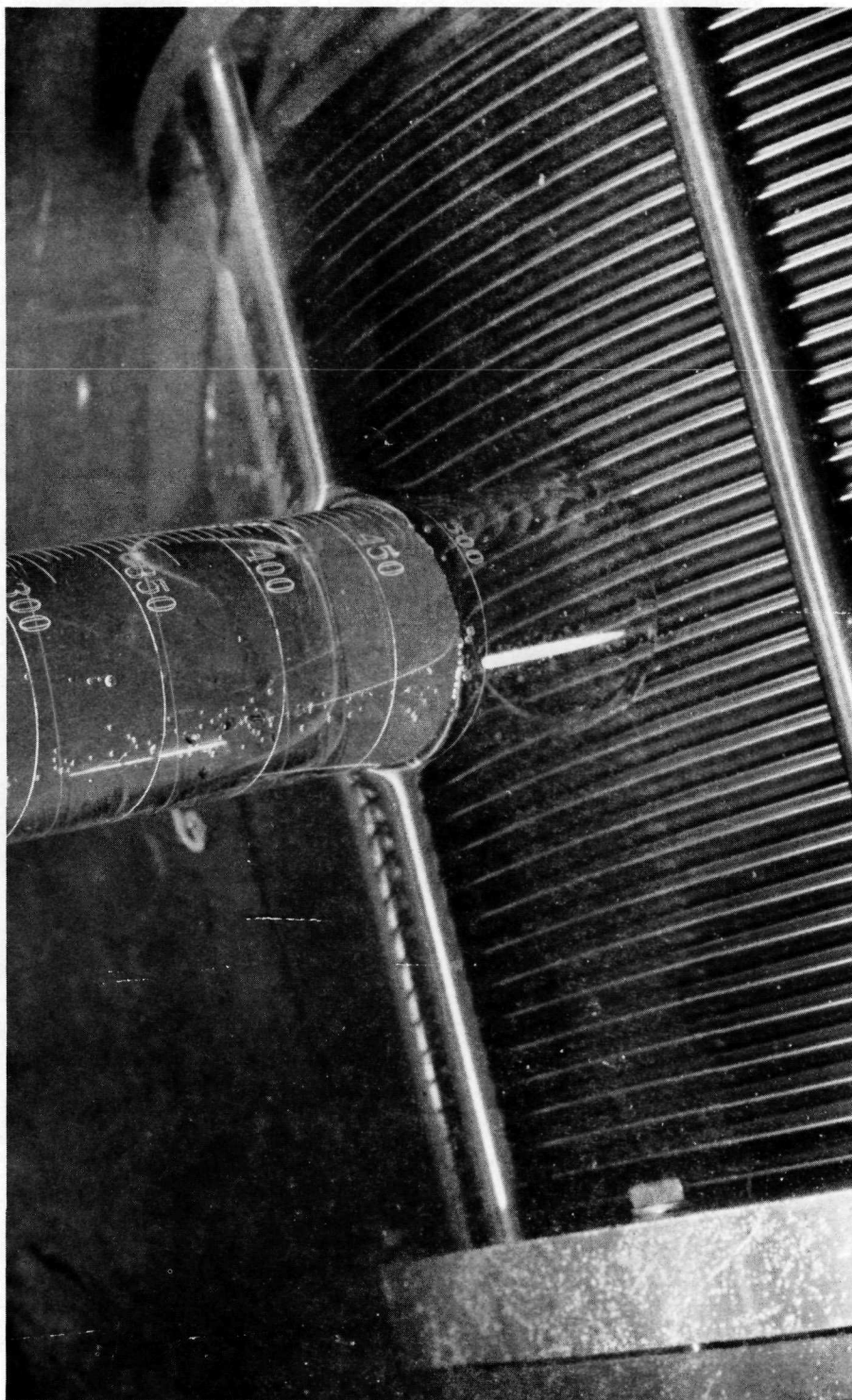


Figure 67 Bellows Cracks Undergoing Leak Check

Also five separate leaks were identified in one of the longitudinal weld joints of bellows 8 (only one was identified in the bubble check conducted at low pressure), but the leak in the 20th convolution of the opposite weld joint was not found. Total leakage for assembly 8 is nearly 3 cm³/sec.

One very small leak was found in assembly 6 in addition to the previously identified large leak in the 18th convolution. Total leakage is nearly 1 cm³/sec.

C. EXAMINATION OF FATIGUE CRACKS

Following the leak checks of the three bellows assemblies, bellows 5 and 8 were cut from the assemblies near the circumferential weld joints and subjected to a metallurgical failure analysis. An unused (noncycled) bellows, cut from one of the first three assemblies fabricated by DK-Aerospace, was also subjected to the same examination to obtain comparative data. Assembly 6, the second one that was tested in fluorine, was left intact, but it could be subjected to failure analysis at a later date if necessary.

It was hoped that a metallurgical examination of the cracks might provide clues regarding the influence of fluorine on crack growth. If not, at least some insight would be gained regarding the general nature of the cracks and their propagation characteristics. A typical surface crack as observed under the stereomicroscope is shown in figure 68.

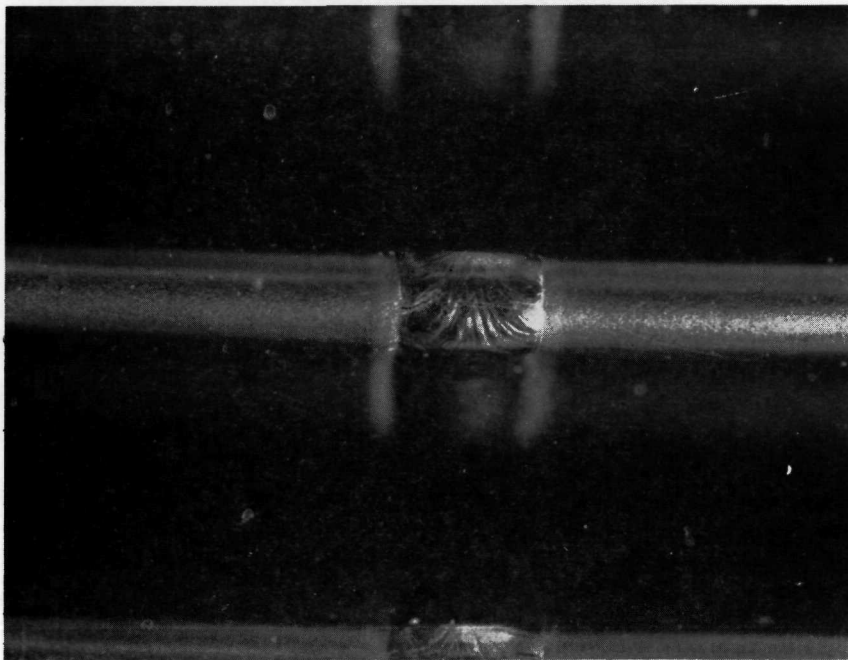


Figure 68 Typical Crack in Bellows Convolution

The specimens were prepared for metallurgical examination by first cutting longitudinal strips (containing the weld joints) from the bellows, and then mounting the strips in 322 Epoxy. Finally, the strips were sequentially ground and polished to the approximate center of the weld joint, and examined under a microscope. Some specimens were examined in the polished condition, others were etched to show the granular structure of the material. Photomicrographs were taken to show regions of particular interest.

Cross sections of two typical convolutions from the noncycled bellows are shown in Figures 69 and 70 at 250X magnification. One of these shows a polished surface, the other an etched surface. Both show evidence of very small surface cracks (initiators) on the inside surface that apparently were generated during forming of the convolutions. These could be expected to propagate inward from the surface if subjected to large cyclical stresses. No cracks, however, were observed on the exterior surface of the weld joint. Note that the polished specimen reveals the cracks more clearly than the etched surface.

Cross sections of typical convolutions from bellows 5 (cycled in LN_2) are shown in figures 71 and 72 at 200X magnification. Several fairly deep cracks are observed in each convolution, undoubtedly cracks that started from small initiators such as those shown in figures 69 and 70, and propagated part way through the material as a result of repeated cycling.

A cross section of the weld joint in convolution 18 is shown in figure 73 at 300X magnification. The crack propagated all the way through, confirming the results of the earlier leak check. The thickness of the material is significantly less for this convolution (300X magnification) than the one shown in figure 71 (200X magnification).

Cross sections of typical convolutions from bellows 8 (cycled in LF_2) are shown in figures 74 thru 78, the majority at 200X magnification. The 20th convolution is shown in figure 74. At this particular section the crack does not appear to have propagated all the way through, but it possibly does penetrate to the outer surface at an adjacent cross section. This convolution did not leak during the leak check, however.

Convolution 21 is shown in figure 75. Again the crack does not appear to have penetrated to the exterior surface, but apparently it does penetrate at an adjacent section because a leak was detected through this convolution.

Convolution 22 is seen in figure 76. Obviously the crack has fully penetrated the weld joint, although a leak was not detected through this convolution. Note, however, that the leak check was performed with the bellows in the fully extended condition, and this may have resulted in the two surfaces of the crack effecting a reasonably good seal near the outer surface of the convolution.

Convolution 25 is shown in figure 77, evidently a case where no significant crack propagation has occurred. This is consistent with the results obtained from the leak check.

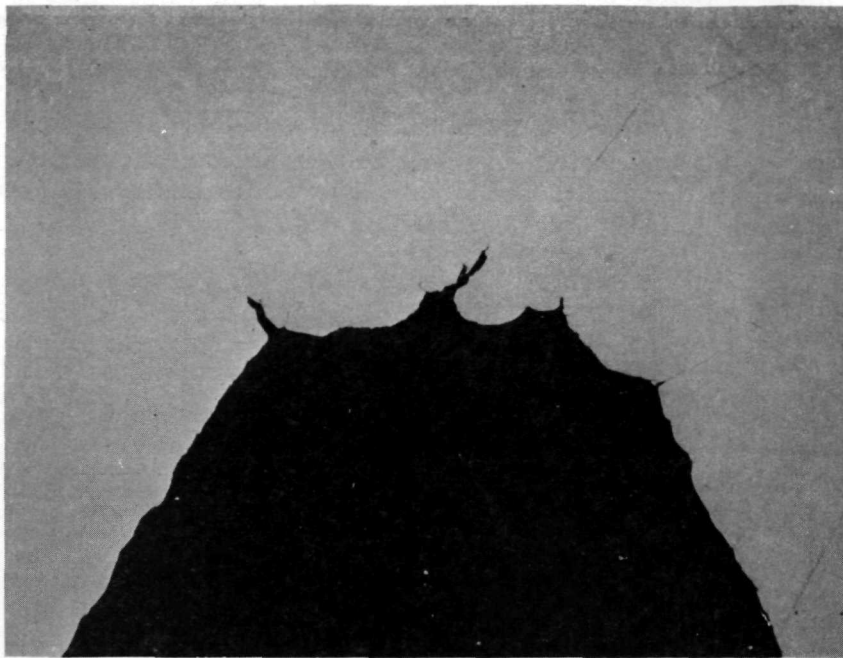


Figure 69 Typical Initiator Cracks (Unused Bellows)

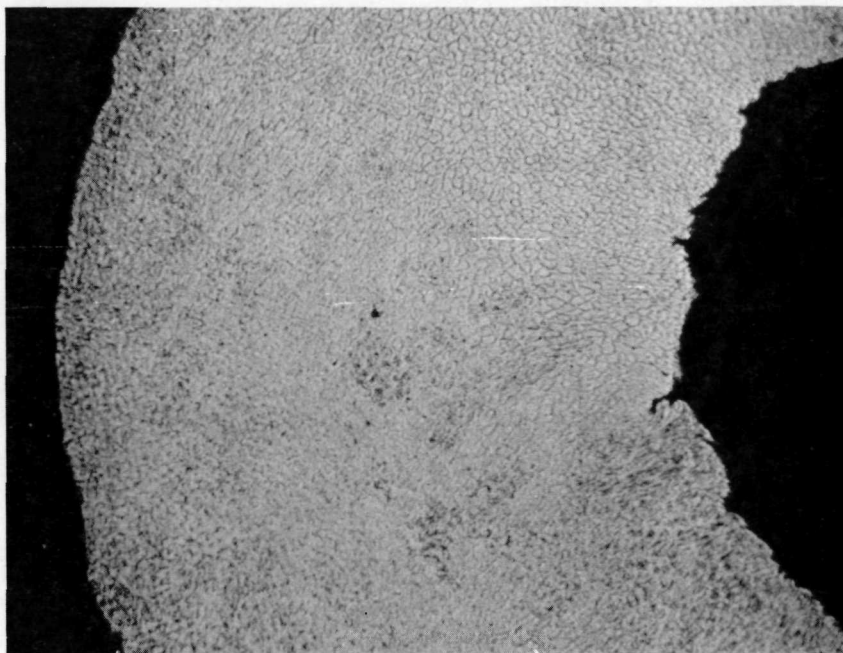


Figure 70 Etched Cross Section (Unused Bellows)

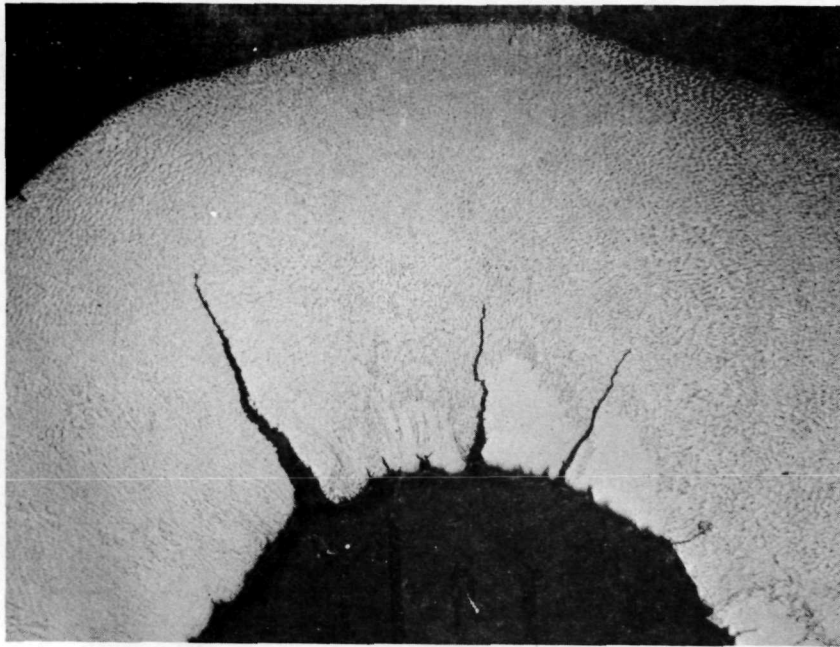


Figure 71 Typical Cracks, Bellows 5

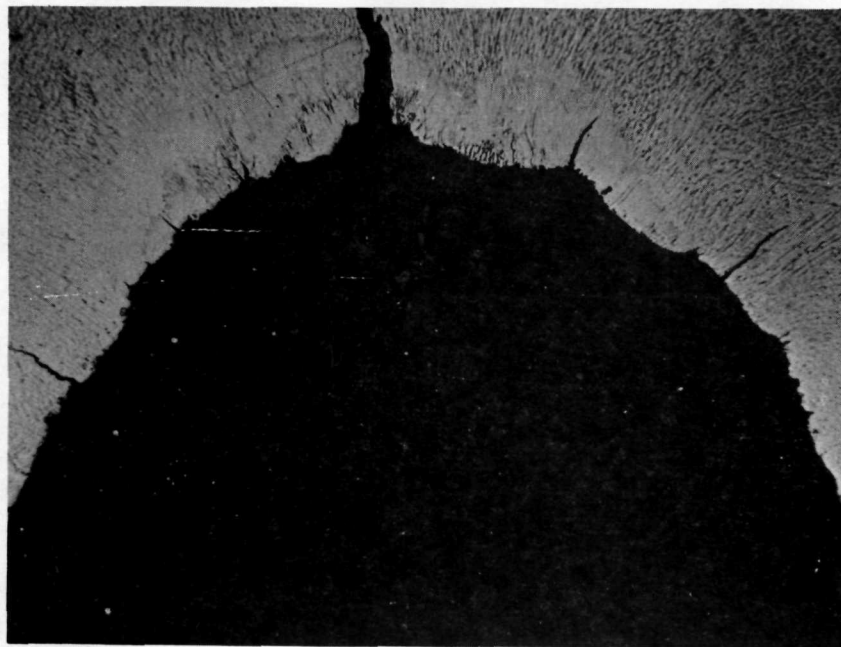


Figure 72 Additional Cracks, Bellows 5

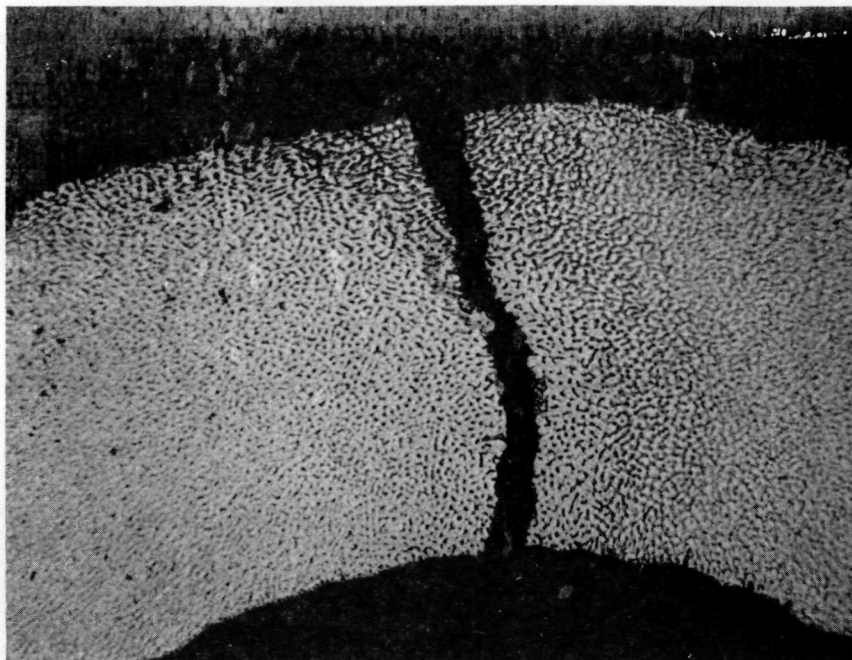


Figure 73 Crack through Convolution 18,
Bellows 5

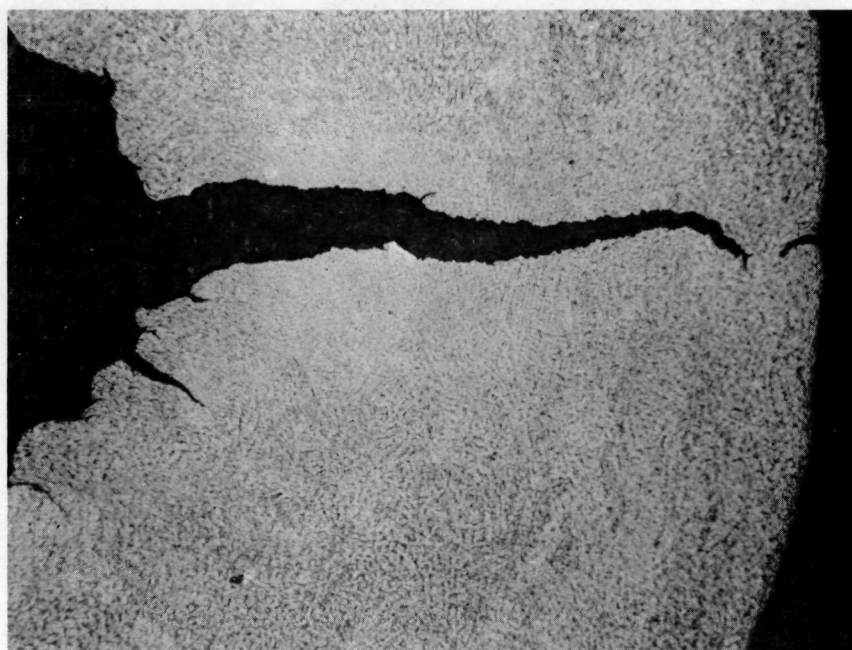


Figure 74 Crack in Convolution 20,
Bellows 8

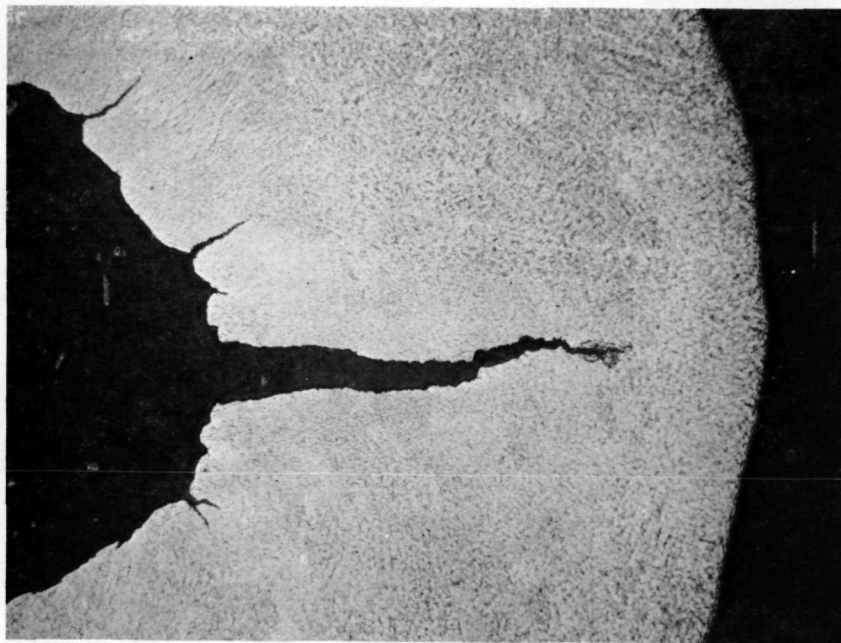


Figure 75 Crack in Convolution 21,
Bellows 8

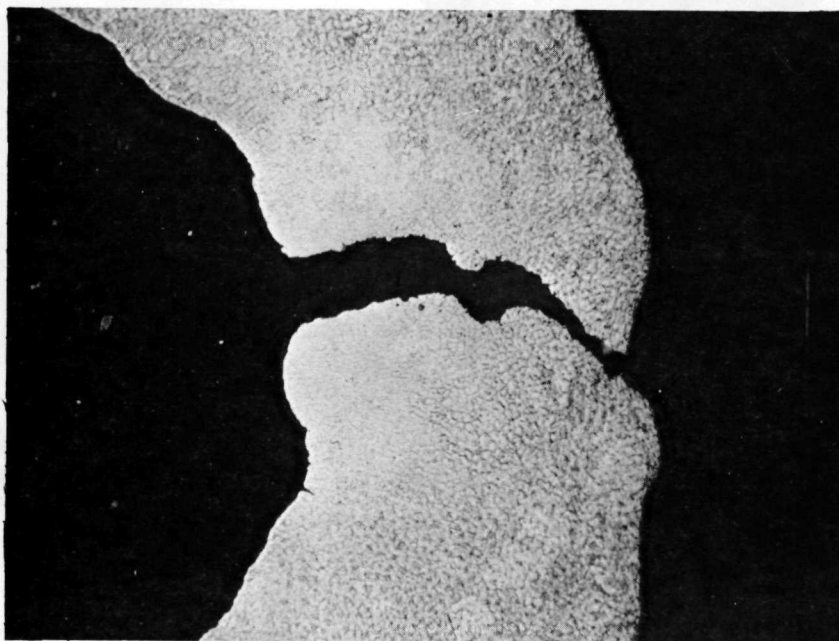


Figure 76 Crack through Convolution 22,
Bellows 8

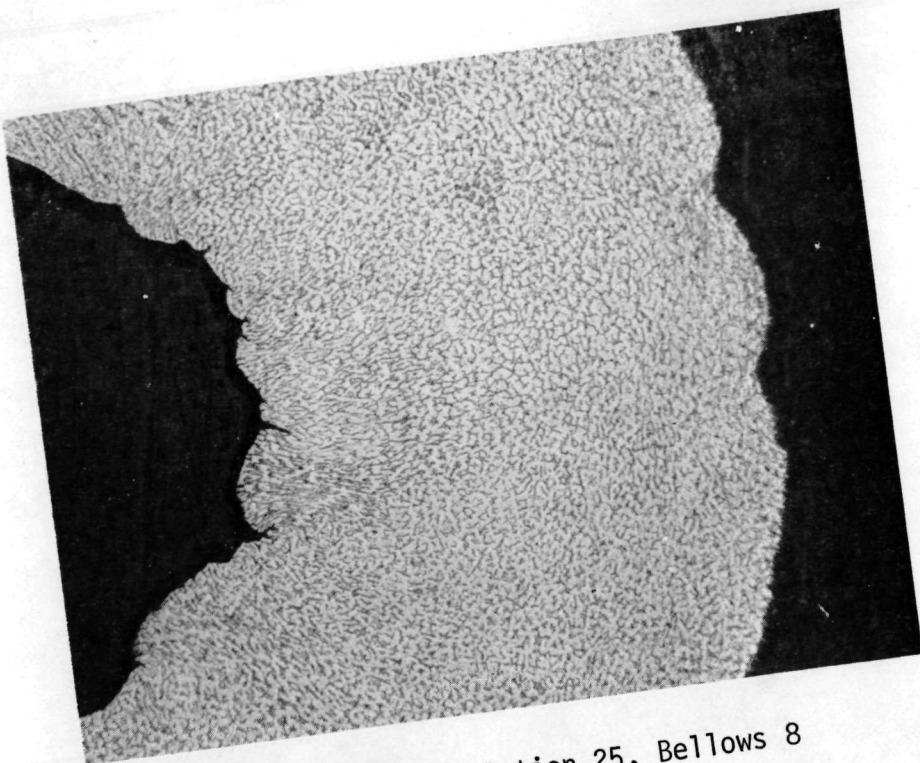


Figure 77 Convolution 25, Bellows 8

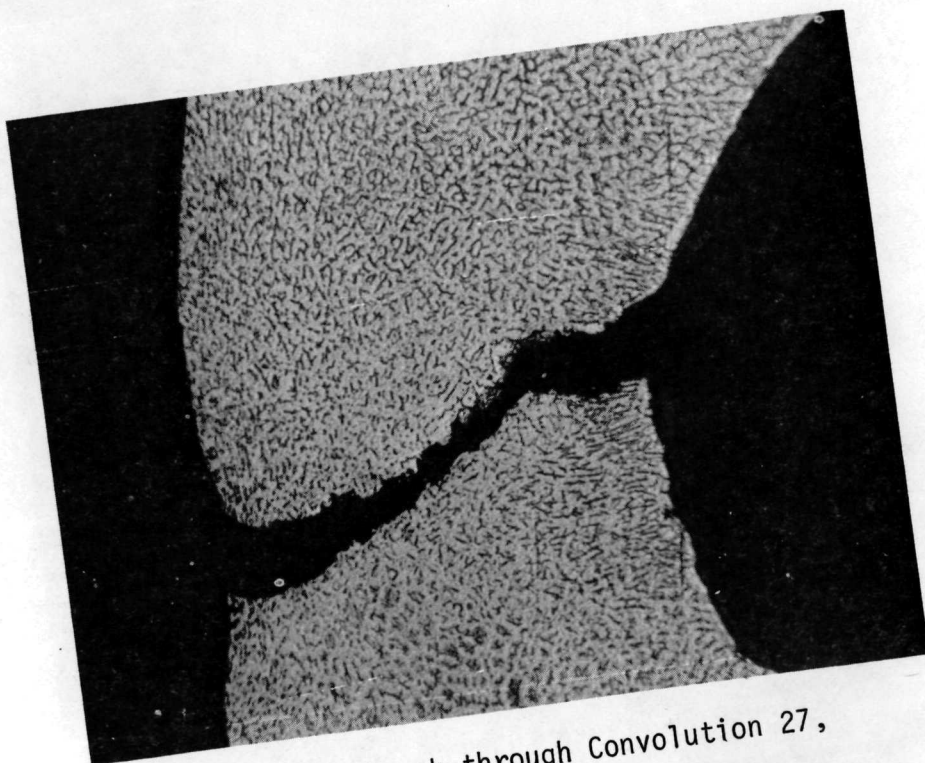


Figure 78 Crack through Convolution 27,
Bellows 8

Convolution 27 is shown in figure 78 at 300X magnification. This crack is very similar to the one found in convolution 22, but its configuration is such that it would not be so likely to seal when the bellows are extended. It did, in fact, exhibit a leak during the leak check. Both convolutions are considerably thinner in the weld zone than those shown in figures 74, 75, and 77.

The photomicrographs reveal a commonality with regard to the direction of the crack growth, i.e., the cracks initiate at the inner surface and propagate to the outer surface. Many crack initiators are noted on the inner surface, but none on the outer surface. No basic difference is found, however, between the cracks in bellows 5 and 8, i.e., the influence of fluorine, if any, is not evident. This result was anticipated at the beginning of the program.

IX. DISCUSSION OF RESULTS

A. OVERALL PERFORMANCE

The most important result of this program was the successful demonstration of the expulsion device to handle liquid fluorine, one of the most difficult of all propellants to manage. The design features incorporated in the device were all state of the art, and fabrication did not require unusually elaborate techniques. Final cleaning of the bellows subassemblies immediately before making the final closure weld, combined with closely controlled operational procedures involving the subsequent use of the completed assembly, proved adequate to assure the degree of cleanliness required for fluorine service. Passivation presented no difficulties, nor did the cycle tests themselves. Filling of the bellows, expulsion, purging, and leak checking were all accomplished without incident, although a small leak did occur at a gasketed joint in the fluorine dewar outlet valve during the initial transfer of fluorine into the test apparatus. The sizable leaks that developed in the bellows during cycling presented no operational problems. The amount of fluorine that leaked through the bellows was so small that its effects were not detectable.

Initially, there was some concern that differential expansion (or contraction) during chilldown and warmup might be a problem, but none materialized. No leakage was ever detected through the gasketed joint of the expulsion device, and there is no evidence that any leaks developed through any of the welded joints (other than the bellows itself). Also, there was no evidence of any binding of moving parts due to distortion or misalignment. The bellows neck did distort slightly when subjected to the proof pressure but this distortion apparently had no effect on bellows performance. No failures (structural or leakage) ever occurred in this region. Except for the failure of the bellows to fully satisfy the design criteria (principally the cycle life), performance of the expulsion device was excellent.

The test installation used in the cycle testing of the bellows also performed admirably. Once the system had been recleaned, it was maintained in a state of cleanliness without any difficulty. The joints in the system did not leak (other than the dewar hand valve), the valves performed perfectly, and the instrumentation proved reliable in providing the required performance data. Several of the remote solenoid valves were operated thousands of times during cycling with no evidence of malfunction. The throttling valve seat was subjected to extremely high fluorine velocities during expulsion at high pressures, but with no adverse effects. In summary, hardware performance was excellent.

B. PERFORMANCE DEFICIENCIES

A comparison of the actual performance of the expulsion device with the original design objectives, reveals that the device fell short of design goals in several respects. The most significant of these failures to achieve the desired performance concerns the bellows cycle life, but the device also failed to provide an expulsion efficiency of 98%, and its performance was very marginal regarding the internal pressure that could be tolerated. Operation at the design working pressure was not actually demonstrated because of the premature fatigue failure of the bellows, though the assembly did withstand proof testing at 175% of the working pressure. Further, the design of the weld joints at the bellows end terminals was unsatisfactory because of the continued difficulties encountered in producing high quality leaktight joints.

Considering each deficiency, it would not be difficult to prescribe appropriate corrective action that would assure compliance with design objectives, except possibly regarding cycle life. The expulsion efficiency, for example can be raised from the measured value of 97.2% to 98% simply by careful control of the critical dimensions of the movable dome, the bellows, and interconnecting parts. The majority of this difference between design and measured performance results because the critical dimensions of the movable dome were not maintained within the required tolerances. This deficiency could probably best be overcome by forming the movable domes from thicker material, then machining the exterior surface to achieve the required clearances. This would accomplish the desired results. In addition, the use of a lap joint at the bellows end terminals to reduce the overall length, plus a reduction in the clearance space between the guide and adapter rings would provide a means of achieving an efficiency greater than 98%.

The marginal performance of the bellows regarding internal pressure probably can not be easily improved without increasing the bellows thickness. A 1-mil (0.025 mm) increase in thickness would be expected to increase critical squirm pressure 50%, but it would further degrade cycle life which is already inadequate. The problem is really not as serious as it might appear, though, because the bellows does not fail at the critical squirm pressure, it only distorts slightly. No distortion was observed at the predicted critical value of 16.5 psig (10.4 N/cm², g), but a very slight distortion was observed at 20 psig (13.8 N/cm², g). The only significant effect of this distortion is a slightly higher stress at some regions in the bellows, and presumably a corresponding decrease in cycle life. This effect is almost undetectable unless the critical pressure is exceeded by a sizable amount.

Regarding the failure of the tests to demonstrate satisfactory performance at the design expulsion pressure, it can only be said that there is no reason to believe that performance at 150 psig (103 N/cm², g) would not have been satisfactory. Bellows 5, however, was subjected to expulsion pressures as high as 130 psia (90 N/cm²) in LN₂, and bellows 6 withstood pressures as high as 110 psia (76 N/cm²) in LF₂. During the expulsion stroke the bellows itself is subjected to only a very small differential pressure up to the point where the movable dome seats in the end dome. At this point, with the bellows in

the compressed condition, the full working pressure is imposed on the bellows exterior, tending to collapse it, particularly in the neck section. To what degree the resulting stresses are additive to those that are instrumental in developing the fatigue cracks at the convolutional crests is not known, but it is not believed that cycle life is a significant function of working pressure in the range being considered here. Bellows 6 was subjected to cycling at considerably higher expulsion pressures than bellows 8, but exhibited essentially the same cycle life. In fact, the leaks that developed in bellows 6 were not as extensive as those in bellows 8.

The most serious problem that plagued the program was the leakage failure of the welds between the bellows and its end terminals. These poor weld joints were the cause of several major slippages in the program. There was considerable concern whether DK-Aerospace would be able to deliver a sufficient number of leaktight assemblies to support the program. In the end, three acceptable assemblies (out of nine welded) were delivered, permitting a satisfactory program to be completed.

The precise cause of these failures is not fully understood, but appears to be a combination of effects, i.e., deficiencies in joint design, weld tooling, and weld technique. The only satisfactory method of correcting this deficiency would be to redesign the joint and develop different tooling. One approach would be to design the joint so that it could be welded from the inside instead of the outside. This would provide much better access for the welding tip, and with properly designed tooling, should overcome the difficulties experienced with the present joint.

An approach preferred by Martin Marietta however, would be to switch from a butt joint to a lap joint of the type proposed for the base design (Alternate C) shown in figure 1. With this approach a satisfactory lap joint can be developed with a minimum of effort. Several sample joints of this type have been welded by Martin Marietta using 5-mil (0.125 mm) material, and they appear to be excellent in all respects. The lap joint is inherently a better joint to weld because the heat is readily dissipated into the bulk of the end terminals without the need for elaborate chill devices, thereby minimizing the danger of burning the thin gage material. In addition, the proposed lap joint offers several other advantages:

- 1) The weld would be made from the inside, thereby providing the "cleanest" possible surface for exposure to the fluorine;
- 2) The bellows neck could be made as short as desired so that buckling of the neck would not be a problem;
- 3) The entire bellows assembly would be shortened 3/8 in. (9.5 mm) at each end, resulting in a slightly smaller and lighter assembly, and a significant reduction in trapped liquid volume (increase in expulsion efficiency);
- 4) Considerable porosity in the end terminal material could be tolerated, because the leak path through it is much longer than it is for the thin section of the butt joint.

The only obvious disadvantage of the lap joint is that it presents a crevice on the outside surface of the bellows. This region is subject to contamination and difficult to clean. Conversely, the crevice is never exposed to fluorine unless the bellows develops a leak, and the design must preclude this possibility. If the external crevice presents a compatibility problem because of the leakage of a significant quantity of fluorine, the entire pressurization system presents an even greater problem. Minute leaks in either case, will be highly diluted and will not present serious problems.

C. CYCLE LIFE

Other than the leaky joints experienced between the bellows and the end terminals, the only serious deficiency in the performance of the expulsion device was the very low cycle life. A compromise regarding cycle life was accepted early in the program when tests conducted by DK-Aerospace indicated that the life for the specific configuration finally selected might be expected to be as low as 400 cycles, rather than the design goal of 1000 cycles. At the time, this did not appear to be a serious limitation because 400 cycles still represented a 4-to-1 safety factor for the number of fluorine cycle tests actually planned.

Even after conducting the LN_2 cycle tests, cycle life did not appear to be a major problem. The bellows did develop a small crack in ~250 cycles, but this was not too far from predicted performance. However, failure of two of the bellows to survive 50 cycles in fluorine certainly was not expected. Apparently the relatively large leaks that developed did not create hazardous operating conditions, but these leaks could not be tolerated in a piece of operational hardware, particularly a flight article.

The cause of these premature failures is not fully understood, though an extensive failure analysis was conducted as previously described. There is an order-of-magnitude difference between the cycle life predicted (based on cycle tests conducted at ambient temperature), and that actually obtained with an expulsion device operating with liquid fluorine. The chemical reactivity of fluorine could not be expected to have a beneficial effect on cycle life, but the question still remains whether this factor alone is responsible for the drastic difference between predicted and actual performance. Other factors that may be at least partially responsible for the short cycle life include the following:

- 1) Cryogenic Temperature - the mechanical properties of 300 series stainless steel are known to change significantly between ambient and cryogenic temperatures. Material strength (both ultimate and yield) improves at cryogenic temperature, while elongation decreases somewhat. The resultant effect on bellows cycle life is difficult to predict, particularly in view of the fact that some regions of the bellows are usually stressed beyond yield during each cycle. The test data generated in this test program would seem to indicate a degradation in performance at cryogenic temperatures, but these data are inadequate to permit firm conclusions to be drawn;

- 2) Working pressure - At the end of the expulsion stroke, the exterior of the bellows (in a positive expulsion device) is subjected to the full working pressure, developing stresses that are additive to those resulting from straining the material. Whether this effect is significant is not known, but it certainly could not be expected to improve cycle life;
- 3) Mechanical characteristics - Significant stresses may be introduced into the bellows as a result of a poor fit of the components of the expulsion assembly. A particularly critical problem is to maintain the proper compressed length of the bellows so that it is not crushed at the convolution roots and crests. Another area of concern is the concentricity of the domes, bellows, and interconnecting hardware. These problems are not encountered to the same degree in "stroking" the bellows in a special fixture.

Regardless of the numerous possible causes of degraded performance, the most obvious action for improving cycle life is to use a seamless, instead of seam-welded tube for the bellows, though this is an added cost. It is natural to expect that the seam weld would be the weakest region in the bellows, and experience has verified that this is the case. It was predicted at the beginning of the program that the bellows would fail first in the seam, and this proved to be the case for all three bellows. In fact, all of the cracks that were identified in the three bellows during the posttest leak checks were in the weld joint, none in the parent metal. Quantitative data were not available regarding the cycle life of seamless vs seam-welded bellows, but there is a significant difference. It is quite possible that this difference (ratio of cycle life) is not a simple constant, but a function of other factors. For example, the ratio of cycle life for a bellows exposed to fluorine might be entirely different from one exposed only to an inert atmosphere.

A second possible approach to increasing the cycle life would be to reduce the stroke per convolution. Such a change, however, can not be effected without certain disadvantages. The bellows becomes longer and heavier, and the expulsion efficiency is decreased as a result of the larger volume of trapped liquid. A careful tradeoff of these factors would have to be considered.

A third possible approach to increasing the bellows life would be to decrease the bellows thickness. The 7-mil (0.18 mm) thickness selected was based primarily on the stiffness needed in the bellows neck to resist buckling. If the entire joint design were changed so that the bellows neck were shortened, a thinner gage material could be used. However, unless other compensating changes were also made, bellows squirming could become a significant problem.

Other avenues for improving performance do exist, but they are not so readily accomplished. A change to a different material such as Inconel 718 should result in improved cycle life, but might also require additional development of tooling. Likewise, a change of the basic bellows configuration (span and contour) could be beneficial, but not necessarily easily accomplished.

X. CONCLUSIONS

From the data accumulated in designing, fabricating, and testing a metallic bellows positive expulsion device for fluorine service, several significant conclusions have been drawn:

- 1) Metallic bellows expulsion devices can readily be designed to function satisfactorily in liquid fluorine (or other highly reactive propellants) in accordance with a rather wide range of performance requirements. State-of-the-art techniques for design, fabrication, cleaning, passivation, and operation of hardware for fluorine service appear to be adequate for the specific case of the metallic bellows;
- 2) The cycle life to be expected from a longitudinally seam-welded bellows does not appear to be accurately predictable. Actual cycle life may be expected to be less than that obtained in simple compression-extension tests conducted in air at ambient temperature, but the relative effects of the bellows operating environment (working pressure, temperature, and chemical reactivity) on cycle life are not accurately known;
- 3) The most promising approach for improving the cycle life of the bellows used in this program is to fabricate the bellows from seamless tubing instead of seam-welded sheet material. All fatigue cracks that developed during the cycle tests were located in the weld joints where many small (initiator) cracks are present as a result of the convolute forming process; no cracks were identified in the parent metal. Suitable seamless tubing can readily be fabricated, but only at considerably greater cost than seam-welded tubing.

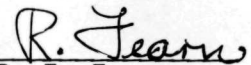
APPENDIX

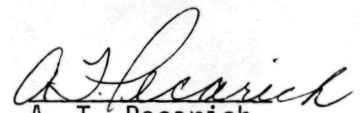
TEST PROCEDURE

TEST PROCEDURE

EXPULSION BELLOWS
LIQUID FLUORINE CYCLES

March 1971


R. F. Fearn
Program Manager


A. T. Pecarich
Test Conductor

APPROVED: 
B. J. Harshman
Safety

- 1.0 OBJECTIVE: The objective of the liquid fluorine cycle test is to determine the cycle life of the expulsion bellows.
- 2.0 TEST EQUIPMENT: The equipment to be used in this test is shown schematically in figure 29 (Chapter V). This apparatus consists primarily of a 40-gallon (0.15 m³) insulated liquid nitrogen tank in which the expulsion device will be installed, a cryostat that contains a 12-gallon (0.045 m³) liquid fluorine supply tank and associated plumbing. Instrumentation will be provided to monitor and control test operations and to record pertinent data. All personnel authorized to work in the test area during liquid fluorine transfer will wear safety equipment, as specified by Safety.
- 3.0 FAILURE MODE:
- 3.1 Electrical Failure: If at anytime during the test, electrical power is lost, the valves in the system will actuate to the positions indicated below:

<u>Valve No.</u>	<u>Function</u>	<u>Position Actuated</u>
4	LF ₂ supply valve	Close
7	Transfer line throttling valve	Close
8	LF ₂ dewar vent valve	Open
9	LF ₂ dewar transfer line vent valve	Open
10	Supply tank vent valve	Open
11	Liquid side of bellows vent valve	Open
13	LF ₂ dewar GHe pressurization valve	Close
15	Transfer line and supply tank GHe purge	Close
16	Supply tank GHe pressurization valve	Close
18	Cryostat LN ₂ supply valve	Open
19	Insulated tank LN ₂ supply valve	Open
22	Vent stack propane supply valve	Close
23	Vent stack purge valve	Close
26	40-gallon (0.15 m ³) insulated tank drain valve	Close
28	Pressure side of bellows vent valve	Close
29	Pressure side of the bellows GHe purge and pressurization valve	Close
30	Liquid side of the bellows GHe purge and pressurization valve	Close

3.2 Pneumatic Failure: If at any time pneumatic pressure is lost, the valves in the system will all actuate CLOSE.

4.0 GENERAL INFORMATION:

4.1 Bellows Overpressure: At no time during the test shall the pressure on the liquid side of the bellows assembly exceed the pressure on the pressure side by more than 15 psi (10.3 N/cm^2).

4.2 Purge and Pressurization Gases Pressures: At all times during the test the pressurization and purge gases upstream of their respective shutoff valves shall always exceed the downstream pressure. This precaution shall be taken to prevent any fluorine gas from back flowing into the purge and pressurization gas systems and contaminating them.

4.3 PA: The PA system to the fluorine cells shall be on at all times during all tests, and the volume set so that all valves may be heard when they are actuated.

5.0 LF₂ SYSTEM LEAK CHECK:

5.1 Notify laboratory personnel--high-pressure gas leak check--area limited access.

5.2 Set facility N₂ and He regulators; 125 psig (86 N/cm^2 , g) max.

5.3 Check all valves closed position.

5.4 Set regulators 1, 2, 3, 12, 34; 50 psig (35 N/cm^2 , g).

5.5 Open valve 29 and pressurize gas side of bellows with helium to 50 psig (35 N/cm^2 , g); close valve 29.

5.6 Open valve 13 and pressurize LF₂ dewar vent line with helium to 50 psig (35 N/cm^2 , g); close valve 13.

5.7 Open valves 4, 15, and 16 and throttle valve 7 until system reaches 50 psig (35 N/cm^2 , g).

5.8 Close valves 15 and 16.

5.9 Leak-check all system connections---fittings, "B" nuts, and flanges---by soap bubble method.

5.10 Close valve 7.

5.11 Open/close valves 10 and 11 to vent system pressure to 10 psig (6.9 N/cm^2 , g).

- 5.12 Open/close valve 8 and vent LF_2 dewar vent line to 10 psig (6.9 N/cm^2 , g).
- 5.13 Open valve 28 and vent bellows pressure to 15 psig (10.3 N/cm^2 , g); close valve 28.
- 5.14 Secure facility N_2 and He pressure.
- 5.15 Secure control panel, notify laboratory personnel.

6.0 SYSTEM PURGE PRETEST PROCEDURE:

- 6.1 Verify that the test equipment has been leak checked and is pressure tight.
- 6.2 Verify that the helium supply is available at a minimum pressure of 1000 psig (690 N/cm^2 , g).
- 6.3 Open the helium supply shutoff valve.
- 6.4 Set the helium pressure regulator located behind the fluorine high bay cell to 120 ± 10 psig (83 ± 7 N/cm^2 , g).
- 6.5 Set the helium pressure regulator 1, 2, 3, and 12 to 35 ± 5 psig (24 ± 3.5 N/cm^2 , g).
- 6.6 Set the helium pressure regulator 34 to 25 ± 5 psig (17 ± 3.5 N/cm^2 , g).

7.0 SYSTEM PURGE:

- 7.1 General Note: The gases used in the following procedure shall be prefiltered to 100-micron (0.1 mm) level, the hydrocarbon content shall not exceed 0.5 ppm (parts per million) by weight, in terms of n-cetane, and the moisture content shall not exceed 5 ppm by weight.
 - 7.1.1 Gaseous Nitrogen: A source capable of supplying gaseous nitrogen in accordance with MIL-P-27401, type I and paragraph 7.1 at a pressure of 100% of the maximum operating pressure as specified on the applicable system shall be provided.
- 7.2 Purge Procedure:
 - 7.2.1 Open valve 29 and pressurize the gas side of the bellows to 35 ± 5 psig (24 ± 3.5 N/cm^2 , g), then close the valve.
 - 7.2.2 Verify valve 7 is closed.

- 7.2.3 Open valves 4 and 15 and pressurize the system from the dewar to the supply tank to 30 ± 5 psig (21 ± 3.5 N/cm², g).
- 7.2.4 Open valve 9 and vent the system to 5 ± 1 psig (3.5 ± 0.7 N/cm², g).
- 7.2.5 Repeat steps 7.2.3 and 7.2.4 four times.
- 7.2.6 Close valve 4.
- 7.2.7 Open valve 16 and pressurize the supply tank to 35 ± 5 psig (24 ± 3.5 N/cm², g), then close the valve.
- 7.2.8 Open/close valve 11 and vent pressure to 2 ± 1 psig (1.4 ± 0.7 N/cm², g).
- 7.2.9 Slowly open valve 7 and purge the transfer line between the supply tank and bellows assembly with gaseous helium.

CAUTION: While valve 7 is being slowly opened, monitor the Bristol recording the flowmeter data to verify the flowmeter will not overspin.

- 7.2.10 When the pressure in the supply tank has decayed to 5 ± 1 psig (3.5 ± 0.7 N/cm², g), close valve 7 and repeat steps 7.2.7 and 7.2.9 four times.
- 7.2.11 After the fifth purge cycle leave the supply tank pressure at 5 ± 1 psig (3.5 ± 0.7 N/cm², g) by leaving valve 7 closed.
- 7.2.12 Verify valve 11 closed.
- 7.2.13 Open valves 28 and 30 and pressurize the liquid side of the bellows assembly with gaseous helium to 9 ± 1 psig (6.2 ± 0.7 N/cm², g), then close the valves.
- 7.2.14 Open valve 11 to vent the gas from the liquid side of the bellows assembly and at the same time, open valve 29 to pressurize the pressure side of the bellows assembly with gaseous helium.
- 7.2.15 When the pressure on the pressure side of the bellows assembly becomes 10 ± 1 psig (7 ± 0.7 N/cm², g), close valves 11 and 29.
- 7.2.16 Repeat steps 7.2.13 through 7.2.15 four times.

- 7.2.17 After the fifth purge cycle, open valve 30 and pressurize the liquid side of the bellows assembly to 5 ± 1 psig (3.5 ± 0.7 N/cm², g), then close valve 30.

8.0 PASSIVATION PRETEST PROCEDURE:

- 8.1 Notify Safety of intent to test.
- 8.2 Verify that the facility nitrogen supply is available at a minimum pressure of 500 psig (345 N/cm², g).
- 8.3 Verify that the helium supply is available at a minimum pressure of 1000 psig (690 N/cm², g).
- 8.4 Verify that the nitrogen purge regulator for the vent stack and the system is at 80 ± 10 psig (55 ± 7 N/cm², g).
- 8.5 Cap off the vent stack drain; open the propane tank valve and light off the vent stack burner.
- 8.6 Verify that the chains are across both access roads and are up and locked.
- 8.7 Start the flow of propane to the vent stack burner by opening valve 22.
- 8.8 Verify valve 4 is closed.
- 8.9 Set regulators 1, 2, 3 and 34 at 50 psig (35 N/cm², g).
- 8.10 Set regulator 12 at 100 psig (69 N/cm², g).
- 8.11 Open the LF₂ dewar shutoff valve 41.
- 8.12 Open the LF₂ dewar pressurization valve 40.

9.0 SYSTEM PASSIVATION PROCEDURE:

- 9.1 General Note: In any production cleaning and handling procedure it is sometimes impossible to remove all contaminants from any component. Only small quantities of contaminants shall remain after cleaning and, therefore, the heat energy addition from reacting these with fluorine will be minor. Too often this cleaning feature of the passivation process is the prime purpose of passivation. This is an unreliable practice because the predictability of the fluorine reaction products and the reacting energy levels is, at best, very poor; therefore, the use of passivation cleaning could result in damage and/or failure of the system. Passivation then will be employed only after the system has been cleaned for fluorine service.

9.2 Passivation Procedure:

- 9.2.1 Put fluorine cells in a RED condition and make the following announcement over the PA: "Attention all laboratory personnel--the fluorine cells are in a RED condition for a fluorine test. All unauthorized personnel stand clear."
- 9.2.2 Open/close valve 13 and pressurize the fluorine dewar to 10 ± 1 psig (7 ± 0.7 N/cm², g). Then close the valve.
- 9.2.3 Pressurize the supply tank with gaseous fluorine to 8 ± 1 psig (5.5 ± 0.7 N/cm², g) by cycling valve 4 open and close, as required, until the pressure is achieved.
- 9.2.4 Allow the pressure in the system to stabilize and if required, repeat step 9.2.3 until the specified pressure is achieved.
- 9.2.5 Hold the 8 ± 1 psig (5.5 ± 0.7 N/cm², g) pressure in the system for 5 minutes (300 sec). Monitor the system pressure for any indication of leaks and/or fire.

NOTE: A fire is indicated in the system when valves 4 and 10 are closed and the Bristol recording the supply tank pressure indicates a pressure increase; and a leak is indicated when the recorder indicates a pressure decrease.

- 9.2.5.1 If valves 4 and 10 are closed and the Bristol recording the supply tank pressure indicates a pressure increase above 50 psig (35 N/cm², g), immediately open valve 10 and 16 and purge the system until all the fluorine in the system has been removed.
- 9.2.5.2 If valves 4 and 10 are closed and the Bristol recording the supply tank pressure indicates a pressure decay, close valves 40 and 41 and then perform a leak check as required to locate the leak.
- 9.2.6 At the end of the 5-minute (300 sec) hold period, open valves 23 and 10 and vent the supply tank to 2 ± 1 psig (1.4 ± 0.7 N/cm², g), then close valve 10. When the vent stack burner has burned the gaseous fluorine, close valve 23.
- 9.2.7 Pressurize the system with gaseous fluorine to 15^{+5}_{-0} psig ($10.3^{+3.5}_{-0}$ N/cm², g), by cycling valve 4, open and close as required, until the pressure is achieved.

- 9.2.8 Allow the pressure in the system to stabilize, and if required repeat step 9.2.7 until the specified pressure is achieved.
- 9.2.9 Hold the pressure in the system for 30 minutes (1800 sec). Visually monitor the system for any indication of leaks and/or fires.
- 9.2.9.1 Repeat step 9.2.5.1 for a fire.
- 9.2.9.2 Repeat step 9.2.5.2 for a leak.
- 9.2.10 After the 30-minute (1800 sec) hold period, repeat step 9.2.6.
- 9.2.11 Repeat steps 9.2.7 through 9.2.9 for a pressure of 25^{+5}_{-0} psig ($17^{+3.5}_{-0}$ N/cm², g) and a hold period of 1 hr (3600 sec).
- 9.2.12 Open valves 11 and 22 and vent the liquid side of the bellows assembly to 2 psig (1.4 N/cm², g), then close valve 11.
- 9.2.13 Open valve 28 and then slowly open valve 7 and pressurize the liquid side of the bellows assembly without gaseous fluorine to 5 ± 1 psig (3.5 ± 0.7 N/cm², g), then close valves 7 and 28.

NOTE: Monitor the Bristol recording the liquid side of the bellows assembly to verify that this pressure does not exceed the pressure on the pressure side of the bellows assembly by 10 psi (6.9 N/cm²).

CAUTION: While valve 7 is being slowly opened, monitor the Bristol recording the flowmeter data to verify the flowmeter does not overspin.

- 9.2.14 Hold the 5 ± 1 psig (3.5 ± 0.7 N/cm², g) pressure in the system for 5 minutes (300 sec). Visually monitor the system for any indication of leaks and/or fires.

NOTE: A fire in the system is indicated when valves 7 and 11 are closed and the Bristol recording the liquid side of the bellows assembly indicates a pressure increase; a leak is indicated when the recorder indicates a pressure decay.

- 9.2.14.1 If valves 7 and 11 are closed and the Bristol recording the liquid side of the bellows assembly indicates a pressure increase above 10 psig (7 N/cm², g), immediately open valves 11 and 30.

- 9.2.14.2 If valves 7 and 11 are closed and the Bristol recording the liquid side of the bellows assembly indicates a pressure decay, repeat step 9.2.14.1 to purge the system until all fluorine in the system has been removed. Then perform the leak checks as required.
- 9.2.15 After the 5-minute (300 sec) hold period open valves 11, 23 and 29 and vent the liquid side of the bellows assembly to 2 ± 1 psig (1.4 ± 0.7 N/cm², g).
- 9.2.16 Repeat steps 9.2.13 through 9.2.14 for a pressure of 15^{+5}_{-0} psig ($10.3^{+3.5}_{-0}$ N/cm², g), and a hold period of 30 minutes (1800 sec).
- 9.2.16.1 Repeat step 9.2.14.1 for a fire.
- 9.2.16.2 Repeat step 9.2.14.2 for a leak.
- 9.2.17 After the 30-minute (1800 sec) hold period open valves 11 and 23 and vent the liquid side of the bellows assembly to 2 ± 1 psig (1.4 ± 0.7 N/cm², g).
- 9.2.18 Repeat steps 9.2.13 through 9.2.14 for a pressure of 25^{+5}_{-0} psig ($17^{+3.5}_{-0}$ N/cm², g), and a hold period of 1 hr (3600 sec).
- 9.2.18.1 Repeat step 9.2.14.1 for a fire.
- 9.2.18.2 Repeat step 9.2.14.2 for a leak.
- 9.2.19 Repeat step 9.2.17 after the 1-hr (3600-sec) hold period.
- 9.2.20 Close valves 40 and 41 on the liquid fluorine dewar.
- 9.2.21 Leave a 5 ± 1 psig (3.5 ± 0.7 N/cm², g) pressure of gaseous helium locked up in the system until ready to proceed with Section 10.0.

10.0 LF₂ DEWAR TO SUPPLY TANK TRANSFER:

10.1 Notify Safety for clearance.

10.1.1 Pretest check of conditions--test conductor and Safety representative (TV cameras and safety equipment operation)--600-gallon (2.3 m³) LN₂ dewar full.

10.1.2 Arm facility deluge system.

- 10.1.3 Notify laboratory personnel--area RED condition--establish road blocks.
- 10.1.4 Control panel and valve position check (all valves closed) and system pressurized to 10 psig (7 N/cm^2 , g). Make sure DP-21 reads 15 psig (10.3 N/cm^2 , g) minimum pressure.
- 10.1.5 Start all recorders and verify all pens are writing.
- 10.2 Set facility N_2 and He regulator pressure; 125 psig (86 N/cm^2 , g) maximum.
 - 10.2.1 Set regulators 1, 2, and 3, at 50 psig (34.5 N/cm^2 , g).
 - 10.2.2 Set regulators 12 and 34 at pressures to meet test requirements.
 - 10.2.3 Set pressure on 600-gallon (2.3 m^3) LN_2 dewar 15 psig (10.3 N/cm^2 , g) maximum. Open manual LN_2 supply valve on 600-gallon (2.3 m^3) dewar.
- 10.3 Cycle valves 13 and 8, purge LF_2 dewar vent line for 5 minutes (300 sec).
 - 10.3.1 Cycle valves 15 and 9, purge LF_2 transfer line for 5 minutes (300 sec).
 - 10.3.2 Open valve 29, let pressure come to regulator 12 pressure setting, 15 psig (10.3 N/cm^2 , g) minimum, close valve 29.
- 10.4 Open valves 18, 19, and 21, fill LN_2 jackets--adjust pressure through valves 16 and 30 to keep system pressure above 5 psig (3.5 N/cm^2 , g).
 - 10.4.1 Close valves 18 and 19 when LN_2 jackets on supply tank and bellows are full.
 - 10.4.2 Adjust valve 21 to obtain proper flow through the transfer line jacket.
- 10.5 Open valves 4 and 10, vent system, pressurize to 1 psig (0.7 N/cm^2 , g). Close valves 10 and 4.
- 10.6 Open LF_2 dewar manual valves 40 and 41.
 - 10.6.1 Test conductor check that all personnel clear from test area.
 - 10.6.2 Open valves 22 and 23.

10.7 Open valve 4, start transfer to supply tank--open and close valve 10 to adjust transfer rate, vent to 1 psig (0.7 N/cm^2 , g) minimum.

10.7.1 Cycle valve 13 to adjust LF_2 dewar pressure to accomplish desired liquid level in supply tank.

10.7.2 Close valve 4.

10.7.3 Close valves 40 and 41.

10.7.4 Open valves 15 and 9, purge transfer line clear.

10.7.5 Close valves 8, 22, and 23.

11.0 BELLOWS CYCLING:

11.1 Check initial conditions:

All valves closed;

Pressure regulator 2 set at $10 \begin{smallmatrix} +2 \\ -0 \end{smallmatrix}$ psig $\left(7 \begin{smallmatrix} +1 \\ -0 \end{smallmatrix} \text{ N/cm}^2, \text{ g} \right)$;

Pressure regulator 12 set at 25 psig (17 N/cm^2 , g), or as required;

DP-21 (gas-side bellows) reads ___ psig (depends on test requirements);

DP-20 (supply tank) reads 20 psig (14 N/cm^2 , g);

DP-28 (liquid-side bellows) reads 20 psig (14 N/cm^2 , g).

11.2 Mark and start recorder 4 at slow speed.

NOTE: Mark pertinent events on charts (DP-28) throughout cycling.

11.3 Open/close 29 and/or 16 if necessary to attain conditions specified in 11.1.

11.4 Open 7 slowly to 15% to equalize pressures; monitor DP-22 for overspin.

11.5 Open 28 to vent bellows and initiate flow; watch vent for evidence of GF_2 ; monitor DP-20; when supply tank pressure drops below regulator setting ___.

11.5.1 Open 16 to continue pressurization; monitor DP-21, when bellows seats (extended) ___.

11.5.2 Close 16 to prevent backflow.

11.5.3 Close 28 in preparation for bellows pressurization.

- 11.7 Reposition 7 if necessary to throttle flow.
- 11.8 Open 29 to pressurize bellows and initiate expulsion; monitor DP-20 and DP-22; when flow begins to drop off.
 - 11.8.1 Open/close 10 to prevent excessive vent supply tank pressure and maintain consistent flow rate.
 - 11.8.2 Close 29 to complete cycle.
- 11.9 Repeat 11.5 through 11.8.2 for the desired number of cycles.
 - 11.9.1 Refill LN₂ baths as necessary during cycling.
- 11.10 Close 7 at end of final cycle.
- 11.11 Stop recorders.
- 12.0 PURGE FOR LEAK CHECK:
 - 12.1 Check initial conditions:
 - 12.1.1 All valves closed.
 - 12.1.2 Pressure regulator 2 set at 10 psig (7 N/cm², g).
 - 12.1.3 Pressure regulator 33 set at 10 psig (7 N/cm², g).
 - 12.1.4 Pressure regulator 12 set at ___ psig (depends on test requirements).
 - 12.1.5 Pressure regulator 34 set at 10 psig (7 N/cm², g).
 - 12.1.6 DP-21 (gas side) reads ___ psig.
 - 12.1.7 DP-20 (supply tank) reads 20 psig (14 N/cm², g).
 - 12.1.8 DP-28 (liquid side) reads 20 psig (14 N/cm², g).
 - 12.1.9 Recorders off.
 - 12.2 Start temperature recorder.
 - 12.3 Open 26 to drain LN₂ bath; when LN₂ level drops below dome, allow 5 minutes (300 sec).
 - 12.3.1 Turn on upper heater to 80 volts, after 20 minutes (1200 sec).
 - 12.3.2 Reduce to 50 volts.

- 12.3.3 Turn off upper heater when T/C No. 2 begins to rise.
- 12.3.4 Close 26 when draining is complete, allow at least 30-minutes (1800-sec) drain time.
- 12.3.5 Open/close 29 as necessary throughout 12.3 to keep positive differential pressure on bellows.
- 12.4 Start pressure recorders (2).
- 12.5 Turn on lower heater to 60 volts to accelerate warmup, Monitor bellows pressures and T/C No. 3, when T/C No. 3 reaches ___ °K (depends on test conditions).
 - 12.5.1 Open/close 11 periodically to vent liquid-side pressure down to 2 ± 1 psig (1.4 ± 0.7 N/cm², g).
 - 12.5.2 Turn off lower heater.
 - 12.5.3 Reset regulator 34 to 10 psig (7 N/cm², g). Cycle 30 and 11 to obtain set pressure.
- 12.6 Open 28 to vent helium pressure down to 29 psia (14 N/cm²), liquid-side pressure still 15 psia (10 N/cm²).
- 12.7 Open/close 30 to purge helium into liquid side of bellows (do not leave valve open or F₂ may backflow into helium system).
 - 12.7.1 Open/close 28 to vent gas side of bellows.
 - 12.7.2 Repeat 12.7 and 12.7.1 until bellows seats extended [5 psi (3.5 N/cm²) ΔP, liquid-to-gas].
- 12.8 Open/close 11 to vent liquid-side pressure to 12 to 14 psia (8.3 to 9.7 N/cm²)(bellows still extended).
- 12.9 Open 25 to evacuate bellows. As gas-side pressure drops:
 - 12.9.1 Open/close 11 if necessary to assure liquid-side pressure <14 psia (<9.6 N/cm²).
 - 12.9.2 Close 25 when bellows fully evacuated, allow 10 minutes (600 sec) pumping at indicated pressure of 0 psia (0 N/cm²).
- 12.10 Open 32 to purge GN₂ into gas side to ~20 psia (14 N/cm²).
 - 12.10.1 Open/close 11 to vent excess pressure and seat bellows (compressed).
 - 12.10.2 Close 32 to complete cycle.

12.11 Repeat 12.7 through 12.10.2 to accomplish a second purge.

12.12 Stop recorders.

13.0 BELLOWS LEAK CHECK:

13.1 Check initial conditions:

All valves closed.

Regulator 2 set at 10 psig (7 N/cm², g).

Regulator 12 set at ___ psig (depends on test requirements).

Regulator 34 set at 5-10 psig (3.5-7 N/cm², g).

DP-20 (supply tank) reads 20 psig (14 N/cm², g).

DP-21 (gas side) reads 17 psig (12 N/cm², g).

DP-28 (liquid side) reads 12 psig (8 N/cm², g).

Leak detector properly connected and in operation.

13.2 Mark and start recorders (2) at slow speed.

13.3 Open/close 11 and 28 if necessary to attain conditions specified in 13.1.

13.4 Enter test cell, disconnect heat exchanger from bellows assembly, and connect vacuum line in its place (as quickly as possible).

NOTE: DP-21 no longer reads the bellows pressure.

13.4.1 Open/close 29 to purge helium through line, then--

13.4.2 Cap off the pressurization line.

13.5 Open valve on leak detector and start pumpdown of bellows. Monitor liquid-side pressure and:

13.5.1 Open/close 30 to maintain pressure 12 to 14 psia (8.3 to 9.6 N/cm²). After several minutes when pressure stabilizes--

13.5.2 Shut off helium pressure recorder. Continue to monitor pressure, if necessary.

13.5.3 Open/close 11 to maintain liquid-side pressure 14 psia (9.6 N/cm²).

- 13.6 Calibrate leak detector and continue to monitor pressure until able to obtain a leakrate measurement. Make measurement every 15 minutes (900 sec), until reading is below 10^{-6} scc He/sec (satisfactory), or stabilizes at value $>10^{-6}$ scc He/sec (unsatisfactory).
- 13.6.1 Secure test if unsatisfactory.
- 13.6.2 Proceed as follows if satisfactory.
- 13.7 Close valve on leak detection and shutdown leak detector.
- 13.8 Mark and restart the helium pressure recorder.
- 13.9 Open 35 and pressurize gas side of bellows to 20 psia (14 N/cm^2) (DP-28 will indicate a pressure rise), then:
- 13.9.1 Close 35 to stop helium purge flow.
- 13.10 Enter cell, disconnect vacuum line from bellows and reconnect the pressurization line (heat exchanger) as quickly as possible.
- NOTE: DP-21 will again read the gas-side pressure.
- 13.10.1 Plug the vacuum hose.
- 13.11 Open/close 29 and pressurize bellows to ___ psig (depends on requirements) in preparation for resumption of cycling.
- 13.12 Open/close 11 as necessary to vent liquid-side pressure down to 20 psia (14 N/cm^2) and seat bellows (compressed).
- 13.13 Resume bellows cycling per 11.0.
- 14.0 LF₂ SUPPLY TANK OVERNIGHT SECURE:
- 14.1 Existing conditions--all valves closed, facility N₂ and He pressure on valves, LN₂ jacket of supply tank full, manual drain valve on 600-gallon (2.3-m^3) LN₂ dewar left open to permit remote emergency fill of supply tank LN₂ jacket.
- 14.2 Open valve 16 bring supply tank to 10 psig (7 N/cm^2 , g), close valve 16.
- 14.3 Notify Safety and laboratory personnel--LF₂ test area, RED condition. (LF₂ supply tank full and will be left unattended overnight).
- 14.4 Check facility N₂ and He pressure left on all remote controlled valves, control panel "ON," all valves indicate "OFF" position.

15.0 LF₂ SYSTEM SECURE - BACK TRANSFER:

- 15.1 Conditions--all valves closed, bellows purged and secured, facility N₂ and He pressure on all remote controlled valves, supply tank pressurized to 10 psig (7 N/cm², g).
- 15.2 Open valves 22, 23 and 21.
- 15.3 Cycle valves 8 and 13, purge LF₂ dewar vent line for 5 minutes (300 sec).
- 15.4 Cycle valves 9 and 15, purge LF₂ dewar liquid line for 5 minutes (300 sec).
- 15.5 Open valves 41 and 40--clear personnel from LF₂ test cell.
- 15.6 Open valve 4 to start transfer, control rate of transfer through valves 16 and 8, maintain LF₂ dewar pressure 5 psig (3.5 N/cm², g) (minimum).
- 15.7 Close valve 4 when transfer is completed as indicated by the liquid level sensor in the supply tank.
- 15.8 Close valves 40, 41 and 21, clear personnel from test cell.
- 15.9 Open valves 15 and 9, purge transfer line clear. Close valves 9 and 15.
- 15.10 Check LF₂ supply tank pressurized to 10 psig (7 N/cm², g).
- 15.11 Monitor LF₂ supply tank pressure during initial warmup period.
- 15.12 Secure facility N₂ and He pressure.
- 15.13 Refill cryostat if necessary by opening valve 18.
- 15.14 Notify Safety and laboratory personnel--condition amber, secure control panel.

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